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DEVELOPMENT OF AN ENVIRONMENTAL DECISION-SUPPORT-TOOL TO OPTIMIZE CO-PROCESSING OF WASTE IN THE CEMENT INDUSTRY (LCA4AFR)

Schlussbericht

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Vorwort zum Schlussbericht

In this project, waste co-processing in the cement industry was analyzed with regard to the ecological implications on clinker production and on waste management. The main outcome is a decision support tool for industry, authorities and other stakeholders. The project could draw on the results of previous studies carried out at ETH Zurich, which provided valuable building blocks for the model and tool development. Thanks go to Christoph Salzmann, Christian Capello, and Christina Seyler. Ralph Meister is acknowledged for his contribution to the tool implementation.

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Advisory board meetings with the project partners and further stakeholders were held regularly. For their valuable contributions and the fruitful discussions we would like to thank the board members

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Zusammenfassung

Projektziel war die Entwicklung eines Ökobilanzmodells, welches die Umweltauswirkung der Abfallmitverwertung in der Zementindustrie bewertet. Das Tool soll der Entscheidungsunterstützung für den Einsatz von Abfällen in Regionen mit unterschiedlich ausgerüsteten Zementwerken dienen. Auf Basis von input- und technologieabhängigen Massenflussmodellen wurden flexible Ökobilanzmodelle von den verschiedenen Zementöfen erstellt. Die Flexibilität bezüglich Abfallcharakteristiken sowie dem technologischen Standard der betreffenden Anlagen erlaubt Analysen mit höherem Detaillierungsgrad und geringerem Zeitaufwand als dies mit konventionellen Ökobilanzdatenbanken möglich ist. Modelle zu Kehrrichtverbrennungsanlagen und Deponien wurden entwickelt um die Abfallmitverwertung in der Zementindustrie mit traditionellen Abfallverwertungs- und Entsorgungsoptionen zu vegleichen. Das Model zur Zementindustrie kann auch als Basis zur ökobilanziellen Bewertung von Baumaterialien wie Zement oder Beton verwendet werden.

Abstract

Project goal was the development of a Life Cycle Assessment based computer tool to assess co-processing of waste in the cement industry. The model assists the decision-making regarding co-processing of various waste types in regions with different technological standards in cement plants. Input- and technology dependent models were established for different cement kiln systems. The integrated flexibility regarding waste characteristics and technological standard of the respective plants allows environmental assessments with increased levels of detail and reduced time expenditure compared to conventional Life Cycle Assessment studies. Models of municipal waste incinerators and landfills were developed to compare co-processing in the cement industry with traditional waste treatment and disposal options. The co-processing model can further be used as basis to assess the production of construction materials such as cement and concrete.

1. Ausgangslage

The production of clinker, the main component of Portland cement, is very energy and resource intensive. Between 3000 and 6000 MJ of energy and around 1.6 tons of raw materials are consumed per ton of clinker produced (*1*). Clinker is an intermediate product in the cement production process in which the Portland cement is a blend of finely ground clinker, additional mineral components and gypsum. In the clinker production process, limestone and other materials containing calcium, silicon, aluminum and iron oxides are crushed and milled into a raw meal. The heating of the raw meal in the kiln system activates the dissociation of calcium carbonate to free calcium oxide, which then forms with the other oxides several hydraulic compounds. The process is relatively tolerant towards the source of the oxides and process heat. This offers opportunities for fuel and raw material substitution if such can result in lower fuel consumption and emissions. The choice of fuels and raw materials has a large effect on the environmental impact of clinker production. Traditionally, the industry has used fossil fuels, mainly coal and oil, and primary raw materials such as limestone, marl and clay. Since the 1970ies it has become a common practice to substitute wastes for primary resources which is generally referred to as co-processing of alternative fuels and raw materials (AFR) (*2*). In addition to the resource saving effects, AFR co-processing in cement kilns has been advocated because it can be a viable waste management option for hazardous and non-hazardous wastes (*3-6*). The environmental effect of AFR co-processing in different kiln systems is of strong interest to the cement industry and environmental authorities. Such information can be used as decision-support regarding permission and regulations of waste co-processing.

2. Ziel der Arbeit

Goal of the project is the development of an LCA based environmental decision tool for the cement industry. First, it shall asses the substitution of primary resources by various wastes or waste mixes in clinker production. Second, the environmental impact of the co-processing of specific wastes in the cement industry shall be compared to other waste treatment options. The programming of a user-friendly interface enables quick, user-specified assessments by non-LCA experts. Besides the cement industry, various other disposal- or production industries recover energy or materials from waste. A comparison of the benefits from AFR co-processing to other waste treatment industries identifies the environmentally optimal treatment option for each waste type. For each industry, various plant configurations (e.g. energy recovery, flue gas treatment installations) are considered.

3. Methode

In this report, the clinker model is presented in detail[1]. The models of municipal waste incinerators and landfills were developed based on (*7-9*), but are not presented.

Scope of the Clinker Model: Functional Unit and System Boundaries. The cradle-to-gate LCA model contains a mass flow-based model of the kiln system (denoted here as foreground system), LCA data for the material-supply chains and for the disposal of cement kiln dust and bypass dust (background system), and a set of life-cycle impact assessment (LCIA) methods (i.e. environmental indicators) (figure 1-top). The functional unit is the production of 1 ton of clinker. The model focuses on clinker production in the cement kiln and excludes the blending and grinding of clinker and additional mineral components to cement. The chosen system boundary facilitates the comparison of waste co-processing with other waste treatment options, because it focuses on the process in which the wastes are actually consumed. The kiln system model describes the mass-flows of 29 chemical elements from the kiln feed to air emissions, clinker, cement kiln dust and bypass dust. A modular structure has been applied which allows the modeling of various configurations of kiln systems and flue gas treatment technologies. Regular process conditions – excluding kiln warm-up, and operation and process failures - are assumed, as is generally done in LCA. Background LCA data represent the supply chain of resources and auxiliary materials from the ecoinvent database (v2.0) (*10*), and a model for landfilling of cement kiln dust and bypass dust. As generally done in LCA, the burden of waste (i.e. AFR) generation is not attributed to the waste treatment industry, but to the industry that is responsible for its production (*10*). Hence, the supply chain of wastes in the model comprises only waste transport and preparation but not waste production. The LCIA methods comprise CML 2001 (*11*), Environmental Design of Industrial Products (EDIP) 1997 and 2003 (*12, 13*), IMPACT 2002+ (*14*), IPCC 2001 Climate change (*15*), TRACI (*16*), CED (*17*), CExD (*18*), Eco-indicator'99 (EE, HA, II) (*19*), Ecological Footprint (*20*), and Ecological Scarcity 1997/2006 (*21, 22*), as implemented in the ecoinvent database (*10*).

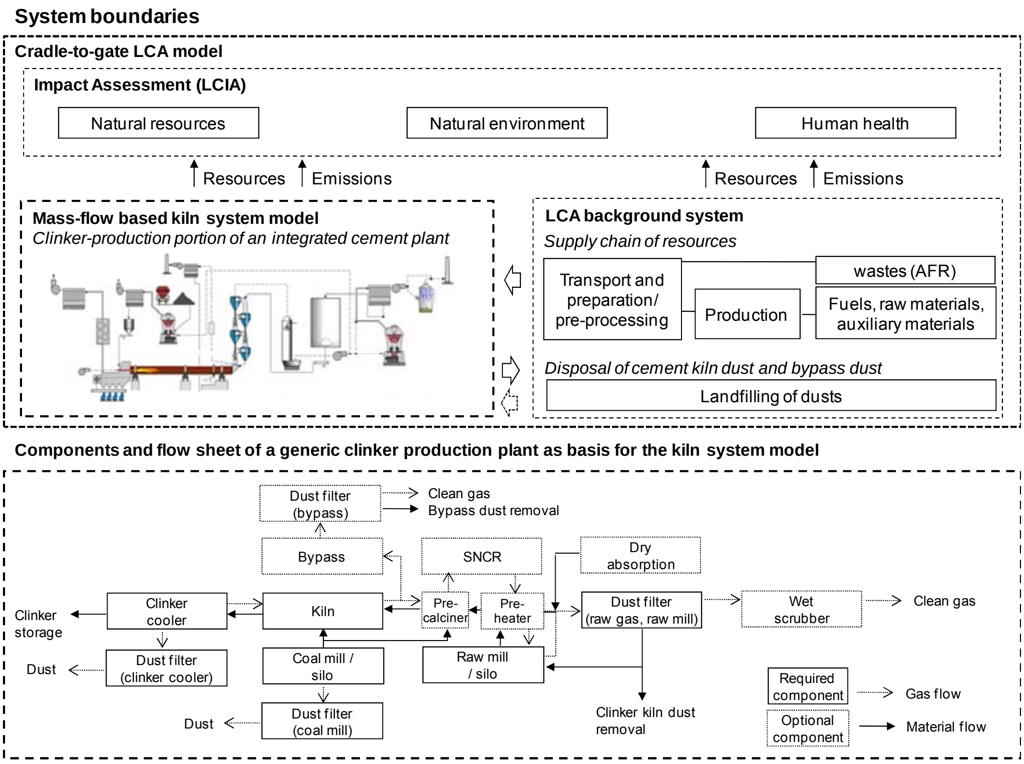

FIGURE 1: Top: System boundaries of the cradle-to-gate LCA model. Bottom: Components and flow sheet of a generic clinker production plant.

[1] The contents of parts of this and the following sections have also been included in a journal publication: Boesch, M.E.; Koehler, A.; Hellweg S.; Model for Cradle-to-Gate Life Cycle Assessment of Clinker Production. Environ. Sci. Technol. 2009, 43 (19) 7578-7683.

Kiln System Model (Foreground System): Plant Layout. Five types of kiln systems are prevalent: Precalciner (PC), Suspension Preheater (SP), Lepol, Long dry, and Long wet (also known as 'wet kiln'). A simplified kiln system layout (applicable to a wet or a long dry kiln line) consists of a rotary kiln, fans, mills for raw materials and fuels, dedusting devices and a stack for the exhaust gas. Current plant layouts feature additional components (e.g. preheaters, precalciners) to increase energy efficiency and reduce environmental impacts. Depending on the kiln system, different components and operation modes are feasible for process and emission control (table 1 and figure 1-bottom; the components and flow sheets of the five kiln systems are shown in Annex 2):

- Preheaters increase energy efficiency by heating the raw meal with kiln gas.
- Precalciners increase energy efficiency by calcining a large fraction of the raw meal in a special combustion chamber between the preheater and the rotary kiln.
- Bypasses are utilized to withdraw excess chlorine from the kiln. Accruing bypass dust has no recycling potential and is removed from the clinker production system to either the cement mill or landfill.
- Compound operation reduces air emissions by leading the raw gas through the raw mill before the stack (primary flue gas treatment). The mixing of the raw gas with the raw meal enhances the retention of particulate and gaseous substances. Dust from compound operation is sent to the raw meal silo. Clinker-kiln dust (dust from direct operation) is either kept in the system (rerouted to the raw meal blending phase or ducted back into the kiln) or removed from the system. If removed, it may be added to the cement mill or landfilled.
- Secondary flue gas treatment comprises, besides dedusting devices (electrostatic precipitators, fabric filters), also NO_x reduction (selective non-catalytic reduction (SNCR)) and SO_2 removal (dry absorption, wet scrubber).

Heat Requirement. Kiln system type, operation and characteristics of fuels and raw materials influence the heat requirement for clinker production (table 1) (*23*). Bypass operation withdraws flue gas from the kiln and is required when chlorine input exceeds the kiln's processing capacity. Surplus oxygen is required to achieve complete oxidation for low grade fuels, and increases by approximately 1% if the relative heat contribution of petcoke and alternative fuels exceeds 30% (*23*). Water and ash in the fuels affect the flame temperature; the ash also affects the chemistry of the system. The lime saturation (i.e. calcium oxide content) and other raw meal characteristics influence the process heat requirement. In the model, the *base heat requirement* quantifies the heat requirement of the kiln system to process the raw meal (*24*). An *additional heat requirement* is calculated from the ash and water content of the fuel mix, bypass operation, and surplus oxygen requirement (table 1) (*23*). Heat and electricity consumption for pre-processing (drying, mixing, crushing and grinding) and for co-processing (feeding to the kiln) of the resources are listed in Annex 3 (*23*).

TABLE 1: Kiln systems and their respective plant components, operation modes, average heat and electricity requirement, and NO_x emissions per ton of clinker.

	Precalciner	**Suspension Preheater**	**Lepol**	**Long dry**	**Long wet**
Plant components and operation modes					
Preheater[a]	√	√	√	-	-
Chlorine bypass	√	√	-	-	-
Compound operation	√	√	-	√	-
Secondary flue gas treatment	√	√	√	√	√
Electricity (kiln system)[b] (average) [kWh/t clinker]	34	34	33	35	35
Base heat requirement, net basis (average (min/max) [MJ/t clinker][c]	3200 (2900/3400)	3400 (3200/3600)	3500 (3450/4500)	5000 (4500/6000)	6000 (5000/6300)
Additional heat requirement, net basis					
Bypass [MJ/% bypass]	10	15	-	-	-
Surplus O_2 [$\%Q_{tot}/\% O_2$] [d]	0.018	0.018	0.018	0.018	0.018
Fuel ash [MJ/kg ash]	1.1	1.1	1.1	1.1	1.1
Fuel H_2O [MJ/kg H_2O]	2.15	2.15	2.15	2.15	2.15
NO_x emissions					
Average NO_x (Stdev)	1.5 (0.5)	1.8 (0.7)	1.9 (0.2)	2.6 (1.2)	3.0 (0.9)

[kg/t clinker][e]
[a]Precalciner and Suspension Preheater kilns systems feature cyclone preheaters. Lepol kiln systems feature grate preheaters.
[b]Electricity requirement among similar kiln systems varies due to technical parameters that are not considered in the model (e.g. dimension of kiln and fans). Average numbers are calculated from a total sample size of 169 production lines (min/max: 18/64 kWh/ t clinker) all being split into different kiln categories.
[c]Base heat requirement includes kiln system and raw material characteristics for the production of grey clinker. The influence of fuel characteristics (ash, water), bypass operation and excess O_2 requirement, by contrast, is summarized under “Additional heat requirement” in the table.
[d]Surplus oxygen is increased by 1% if the relative heat input from petcoke and alternative fuels exceeds 30%.
[e]Average numbers are calculated from a total sample size of 89 kilns.

Mass Flow Model. For the calculation of the distribution of elements from the input to the output streams, the model applies transfer coefficients (TC) for heavy metals and sulfur, and emission factors for carbon, nitrogen, chloride and fluoride compounds and for specific emissions in case of secondary flue gas treatment (NO_x, SO_2, dust). TC quantify the partitioning of each element to flue gas and to solid material (clinker, raw meal, cement kiln dust, bypass dust). TC-based modules are provided for the kiln and precalciner, preheater, raw mill, and dedusting devices of the raw gas and bypass gas (see Annex S2, S4, S5). The TC in each module sum up to 100% for each element. Figure 2 depicts the mass-flow model. Due to the recirculation of elements in the process, induced by the routing of cement kiln dust back to the raw meal silo and due to compound operation, the system of equations, which is applicable to all kiln systems, is circular (see Annex S5 for the mathematical description). For kiln systems without preheater, the transfer coefficient (TC) ‘Preheater (exhaust gas), raw gas’ is set to 100% and the TC ‘Preheater (kiln feed), raw gas’ to 0% for all elements (see dashed box in figure 2 and in Annex S5).

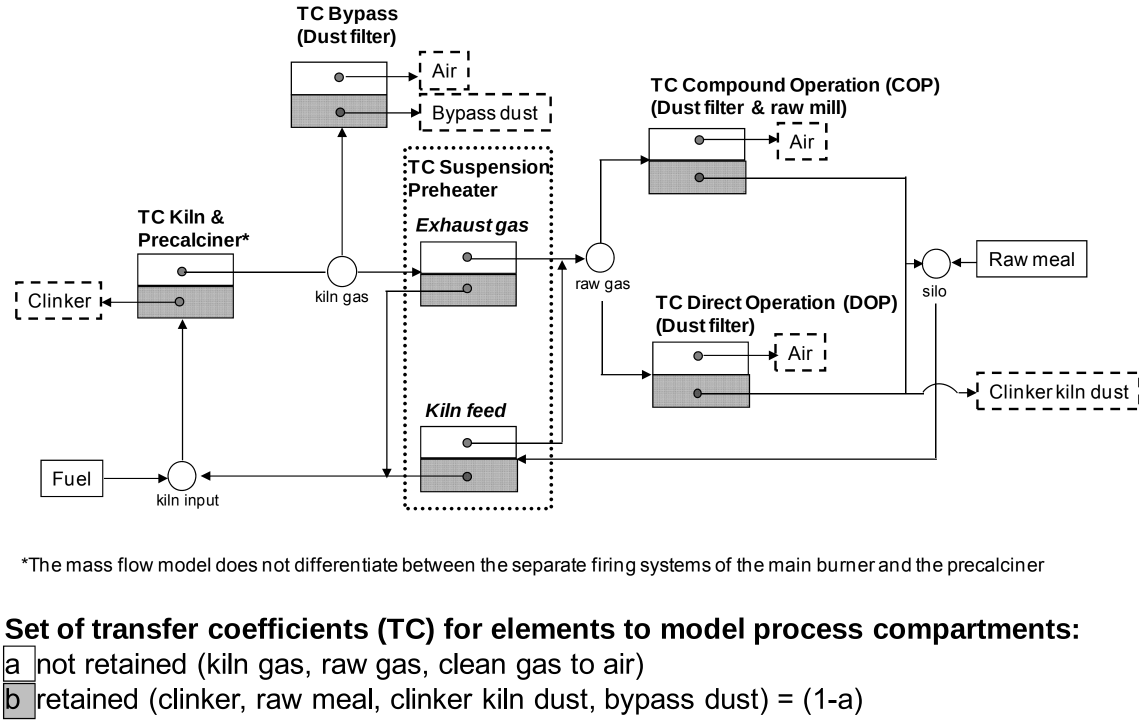

FIGURE 2: Mass flow model of a precalciner kiln system (see Annex 5 for further kiln systems).

Carbon-based emissions originate from the organic carbon and the carbonated CaO and MgO (e.g. $CaCO_3$, $CaMg(CO_3)_2$) in the fuels and raw materials. The model assumes complete calcination of all CaO and MgO in the clinker and bypass dust, which results in calcination CO_2 emissions (*25*). Cement kiln dust in precalciner and suspension preheater kiln systems accrues before the calcination zone of the preheater and remains carbonated (*24*). In Lepol, long dry and long wet kilns, cement kiln dust is partially calcined (50% assumed in the model) (*25*). The model assumes that organic carbon is oxidized and emitted to air in form of CO_2, CO, VOC, benzene, and dioxins (PCDD/F). Traces of PCDD/F can be found in cement kiln dust and are set to 6.7 ng TEQ/kg cement kiln dust in the model (*26*). The concentration of carbon based pollutants in the exhaust gas is set to 1000 mg/Nm^3 for CO, 40 mg/Nm^3 for VOC, 1 mg/Nm3 for benzene and 0.1 ng TEQ/Nm^3 for PCDD/F (average values from (*1, 23*)). The rest of the organic carbon is emitted as CO_2. Nitrogen-based emissions originate from the nitrogen in fuels and raw materials, combustion and excess air, and SNCR reactants. The model considers N_2, NO_x and NH_3 emissions. Emission loads of the greenhouse gas N_2O are extremely low in cement kilns (*27*) and are not specified in the model. If there is no secondary flue gas treatment for NO_x, the pollutant concentration in the exhaust gas is set to 10 mg/Nm^3 for NH_3 and the kiln system average for NO_x (see table 1). The remaining nitrogen is accounted for by N_2 emissions (*28*). Chlorine and fluorine emissions are specified as HCl and HF and set to 2% of total chloride and fluoride input in case of no bypass operation, and to 4% in case of bypass operation (*28*). The model for bypass operation allows for 3%, 5% and 8% of bypassed kiln gas, which entails bypass dust generation of 1%, 1.5% and 2% (relative to clinker production), and chlorine (and fluorine) removal efficiency from the kiln of 85%, 90%, and 95%, respectively (*28*). The remaining Cl and F is allocated to clinker and accruing cement kiln dust according to the respective mass.

In case of secondary flue gas treatment, the model describes a cap modeling, which allows capping the emission levels (set as mg/Nm^3 of exhaust gas) of the controlled substances (NO_x, SO_2, dust). The capped emission levels that can be achieved per flue gas technology for NO_x and SO_2 removal may vary between plants. The SNCR model is set to require an input of 0.2 kg NH_3/t clinker and to increase NH_3 air emissions to 25 mg/Nm^3 due to ammonia slip (*28*). The model requires 10 kg $Ca(OH)_2$/t clinker for dry absorption and an aqueous limestone suspension containing 11.5 kg limestone and 130 kg water for the wet scrubber (*28*). Gypsum is produced as a byproduct of the wet scrubber process, which can be used as additive in the cement mill. The secondary treatment of NO_x and SO_2 does not generate wastewater since the water is completely evaporated. For dust abatement, electrostatic precipitators and fabric filters are modeled. The exhaust gas volume is calculated according to IUPAC standard conditions for gases with T=273.15 K and p=101,325 Pa (*29*). The exhaust gas is specified as dry and with 10% excess oxygen. The exhaust gas consists of compounds originating from the fuels, raw materials, refractory linings, combustion air, and excess air (see Annex 6). However, material contribution from the refractory linings to the exhaust gas was assumed to be marginal and not considered in the model. The chemical composition of ambient air used for combustion and as excess air is assumed to be 21% oxygen and 79% nitrogen. Trace elements are not considered.

Cradle-to-gate LCA Data (Background System). The kiln system model has been supplemented with life-cycle data for the supply chains of resources and operating materials, as well with a disposal model for cement kiln dust and bypass dust. The life-cycle data of fuels, raw materials, and operating material production are taken from the ecoinvent database (*10*). The dust disposal model accounts for leaching of contaminants into surface water in case of removal and landfilling of dusts. The model contains transfer coefficients to the leachate from monitored residual material landfills to approximate leaching of dusts (*8*).

Case Study

Several case studies were computed to assess the environmental impact of waste co-processing. One example will be shown in this report. The basis for the analysis is a cement plant with a precalciner kiln system that co-processes tires, waste rubber, prepared municipal solid waste (RDF, 'Refuse Derived Fuel') and prepared industrial waste. The calculated emissions from the model were compared to measured emissions at the case study plant. The effects of co-processing were analyzed for three alternative fuels (tires, prepared industrial waste, dried sewage sludge) and one alternative raw material (blast furnace slag). Tires, prepared industrial waste and dried sewage sludge substitute hard coal, while blast furnace slag substitutes limestone and clay. Consumption of traditional raw materials was adjusted according to the wastes' mineral composition to ensure constant clinker quality (see Annex 7-10).

4. Ergebnisse

Results of the Case Study

TABLE 2: Life Cycle Impact Assessment (LCIA) of the production of 1 ton clinker. a) Comparison of reported production data with model results; b) Co-processing tires, prepared industrial waste, dried sewage sludge and blast furnace slag in a precalciner kiln system.

	IPCC 2001 Climate Change (100 years) (kg CO_2-Eq.)	**CExD, non-renewable (MJ-Eq.)**	**Eco-Indicator'99 (H,A), total (points)**
a) Predicted vs. measured results			
Reported production data	937	4427	18.07

Model data, base case[a]	944	4550	19.65
b) AFR co-processing in a precalciner kiln system			
+ 20 kg tires, whole	922	4036	19.19
+ 20 kg prep. industr. waste	928	4245	19.41
+ 20 kg dried sewage sludge	941	4516	20.23
+ 20 kg blast furnace slag	937	4542	19.60

[a]All results of b) should be compared to this base case (precalciner kiln system; fuel mix (% heat): hard coal (50.0%), petcoke (22.4%), natural gas (0.8%), prepared industrial waste (10.9%), RDF (13.0%), waste rubber (0.7%), tires (2.2%); raw material mix (% weight): limestone (78.5%), clay (20.3%), iron ore (1.2%). For details on the technical specifications of the plant and fuel and raw material characteristics see Annexes S7, S9).

In the case study, the model mirrors actual production with an error of less than 2% for heat requirement, flue gas volume, and CO_2 emissions. For NO_x, SO_2, NH_3, the error was 33%, 15%, and 9%, respectively. Organic and dust emissions were over-estimated. The accuracy of heavy metal emissions was often rather low (see Annex S9 and Discussion Section). For all LCIA methods applied, the difference of the environmental impact between modeled and actual clinker production was less than 33% (in most cases below 10%, see Annex 9).
For the assessed wastes, co-processing generally reveals a positive effect on the environmental impact of clinker production, albeit due to different reasons (table 2). Tires and prepared industrial waste feature lower CO_2 emission factors than hard coal, and contain 27% and 40% biogenic carbon, respectively. In LCA, biogenic CO_2 is considered climate neutral. Dried sewage sludge is 100% biogenic, but substantial burdens occur in the supply chain due to the energy intensive drying process. The energy consumption for drying overshadows the savings of fossil CO_2 at the plant and leads to a negative result in terms of eco-indicator'99 scores. Blast furnace slag substitutes traditional raw materials. It contains calcined CaO and MgO and hence does not emit calcination CO_2. Further, the slag's low content of organic carbon results in reduced fossil CO_2 emissions (see Annex 10 for inventory data).

5. Diskussion

Applicability of the Model. An LCA-based clinker production model has been presented that allows for environmental assessments of clinker production with various production technologies and as a function of fuel and raw material mixes. It is intended for environmental officers in the cement industry, environmental authorities in the waste sector, and LCA practitioners. Within the cement industry, the model provides insights into sensitivities of various process parameters on the integrated environmental impact of clinker production, and can be applied for decision support regarding the selection of AFR. Environmental authorities may use it to analyze the benefits and burdens of co-processing specific wastes and compare the results with alternative waste treatment options.

Data Quality and Uncertainty. General data are assumed to represent an average situation regarding heat and electricity consumption and resource preparation, as most data are based on first-hand industry information from many plants (n=106). However, as in most LCA studies, there are considerable uncertainties involved in emission modeling. In this context, the IPPC reference document on best available techniques (*1*) provides ranges of pollutant emissions at European cement plants, which can be used for sensitivity analyses (see Annex 9 for the contribution of specific pollutants to total LCIA scores).
The assumption of constant NO_x, CO, VOC, benzene, and dioxins emission concentrations in the exhaust gas is a simplified approach for emissions modeling, and does not take into account the complex thermodynamical situation and the various parameters influencing the formation and decomposition of these compounds. NO_x emissions are influenced by the temperature profile and oxygen content in kiln and preheater, presence of moisture, burner design, reactivity and nitrogen content of fuel, and others (*1*). CO, VOC and benzene emissions are related to incomplete combustion and may increase during start-up or upset conditions, or in case of elevated contents of organic matter in the kiln feed (*1*). PCDD/F emissions (and formation on cement kiln dust particles) are influenced by the content of chlorine and hydrocarbon precursors in the raw meal and the exhaust gas cooling in the air pollution control device (*1, 26*). The modeling of the flue gas treatment technologies also predicts constant emissions for NO_x, SO_2 and dust. In reality, the emissions may fluctuate despite secondary flue gas treatment. However, achieved levels can normally be maintained in a yearly average. Heavy metal emissions can be controlled to a certain degree with the air pollution control device (*5*), but the emission behavior of specific heavy metals may vary significantly from plant to plant. The applied modeling

approaches may result in systematic errors, which are less relevant when the same assumptions are used to compare two production options.

Data consistency on heavy metal mass flows in cement kilns is generally low. There are large uncertainties in the heavy metal content of input materials due to difficulties in obtaining representative resource samples, frequencies of analyses, and measured concentrations close or below the detection limit. In combination with large mass consumptions of resources, especially of raw materials, small errors in the measurement of the heavy metal concentration may result in large errors regarding total heavy metal input. The problem of concentrations close to or below detection limits applies also to emission measurements at the stack. The resulting uncertainties in the heavy metal mass balances may bias the predicted environmental impact of the assessed clinker production options with regard to toxicity-related impact categories.

The model is not intended to monitor compliance with environmental quality standards such as local air emissions, but to assess and compare clinker production options using LCA methodology. Despite uncertainties in the prediction of pollutant emissions, the presented model may improve the accuracy of environmental assessments of waste co-processing, especially for the assessment of future-oriented scenarios, for which no production data are yet available.

6. Schlussfolgerungen

The project demonstrated that the LCA-based model on co-processing is able to identify relevant environmental issues of waste co-processing in clinker production and can be used for decision support. In addition, the co-processing model of the cement industry may be used as basis to assess the production of construction materials such as cement and concrete. The models for co-processing in the cement industry, waste incineration and landfilling were completed. A model for co-processing in the steel industry is under development and will be completed in a follow-up project in collaboration with an industry partner. The development of further models to extend the coverage of waste treatment industries is under discussion. Tools and user manuals will be publicly available on the research group's website in 2010 (http://www.ifu.ethz.ch/ESD/research/TEDST/cement/index_EN). The co-processing model/tool was published in a scientific journal[2] and presented at international scientific conferences[3]. The co-processing tool was applied in a report on scrap tire treatment options in the US by the Center of Resilience[4] and in a report on biomass waste treatment by econcept/ESU service[5]. Currently the co-processing tool is being reviewed by an external consultant company. Presentations and training courses were held for the industry partner and presentations were given to stakeholder representatives (BfE, BAFU, UNIDO, Basel Convention). The project partner is currently establishing case studies at selected cement plants, and after a testing phase worldwide application of the tool is anticipated for group-internal consultancy services and external communication. Public availability of the tool shall facilitate its utilization by industry, authorities, NGOs and further interest groups.

Symbolverzeichnis

Acronyms and abbreviations used in this report are explained in Annex 1.

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Anhang

ANNEX 1: ACRONYMS AND ABBREVIATIONS

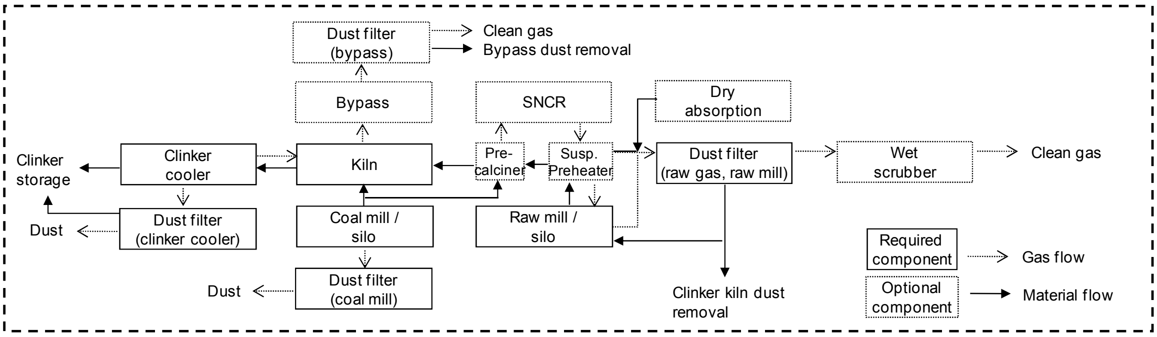
AFR	Alternative fuels and raw materials (wastes)
CExD, non-renewable	Consumption of non-renewable resources according to the LCIA method Cumulative Exergy Demand
CKD	Cement kiln dust
Ecoindicator'99 (H,A), total	Aggregated damage according to default Ecoindicator'99 LCIA method
IPCC 2001 Climate Change, (100 years)	Damage according to the LCIA method by Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
Lepol	Grate preheater kiln system
Long dry	Long dry kiln system
Long wet	Long wet kiln system
NMVOC	Non-methane volatile organic compounds
NOx	Nitrogen oxides
PC	Precalciner kiln system
PCDD/F	Dioxins and furans
RDF	Prepared municipal solid waste ('Refuse Derived Fuel')
SNCR	Selective Non-Catalytic Reduction
SP	Suspension preheater kiln system
TC	Transfer coefficient
TEQ	Toxic Equivalents

VOC	Volatile organic compounds

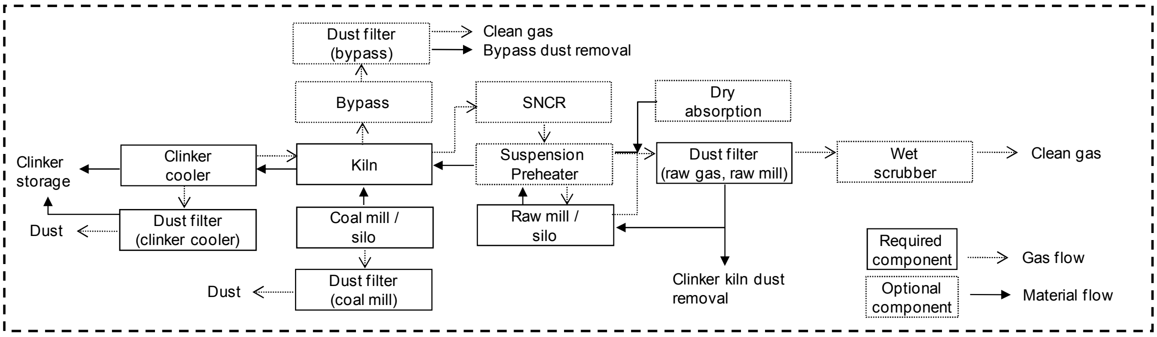
ANNEX 2: COMPONENTS OF KILN SYSTEMS

In the figures, solid arrows represent material flow of clinker material (raw meal, dust, clinker) and of operating material (dry absorption: calcium hydroxide). Dashed arrows represent gas flows from the process. Solid boxes represent required process components, dashed boxes represent optional components.

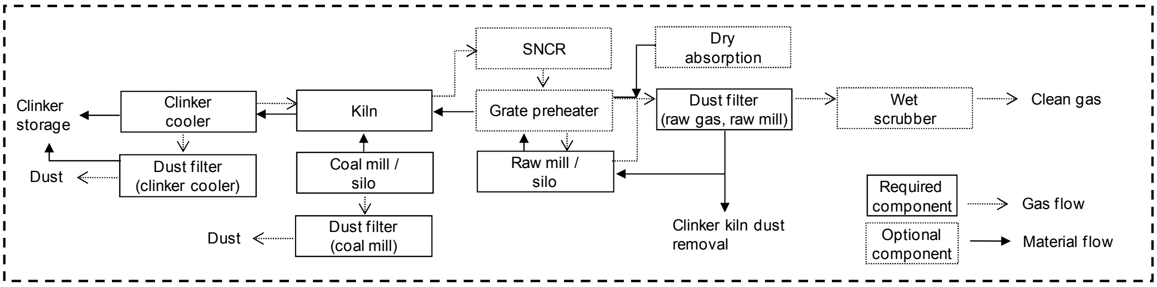
Precalciner kiln system



Suspension preheater kiln system

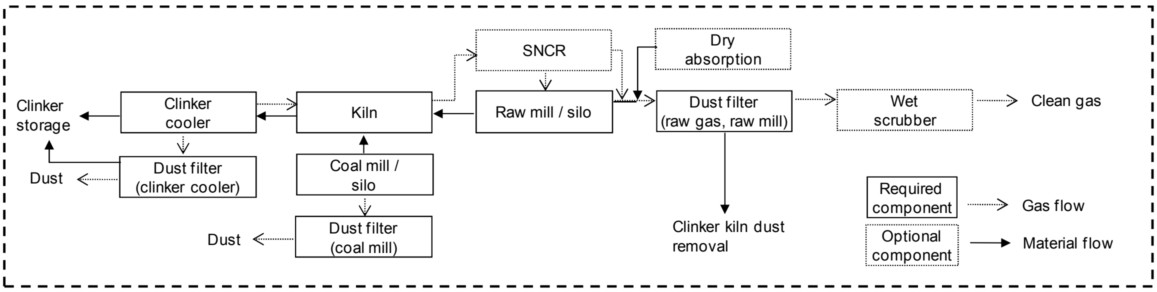


Lepol kiln system (dry system)

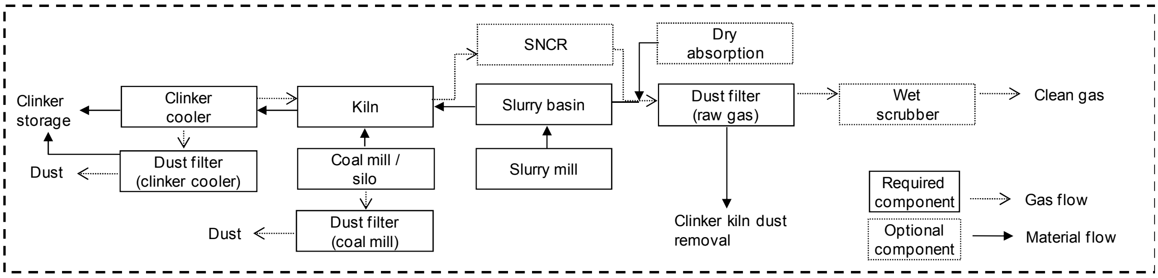


The intermediate step of nodulizing the raw mix before the grate preheater has been omitted

Long dry kiln system



Long wet kiln system



ANNEX 3: ELECTRICITY AND HEAT REQUIREMENT FOR PREPARATION AND FEEDING OF FUELS, RAW MATERIALS, AND WASTES (AFR)

Fuels and raw materials	kWh (electricity) / t	MJ (heat) / t
Traditional fuels		
Hard coal	40	-[a]
Brown coal	35	-[a]
Petcoke	45	-[a]
Heavy Oil	3	200[b]
Alternative fuels		
RDF (refuse derived fuel)	40	-
Prepared industrial waste (containing hazard. waste[c])	45	150
CSS[c]	48	250
Sewage sludge[d]	8	-
Tires (whole/shredded)	3 / 45	-
Waste plastics	43	-
Waste oil	3	-
Waste solvents	3	-
Traditional raw materials		
All traditional raw materials	25	-
Alternative raw materials		
All altern. raw materials	25	-

[a]Waste heat from kiln is used for drying of fuels. Wastes are usually fed to the kiln without drying.

[b] Heat is required to liquefy heavy oil. Waste oil required no heat since it contains various up-graded oils (e.g. motor oils).

[c]CSS (combustible de substitution solide) is a mixture of saw dust with solvents, inert materials and miscellaneous organic compounds. Heat is mainly required for VOC abatement during CSS preparation.

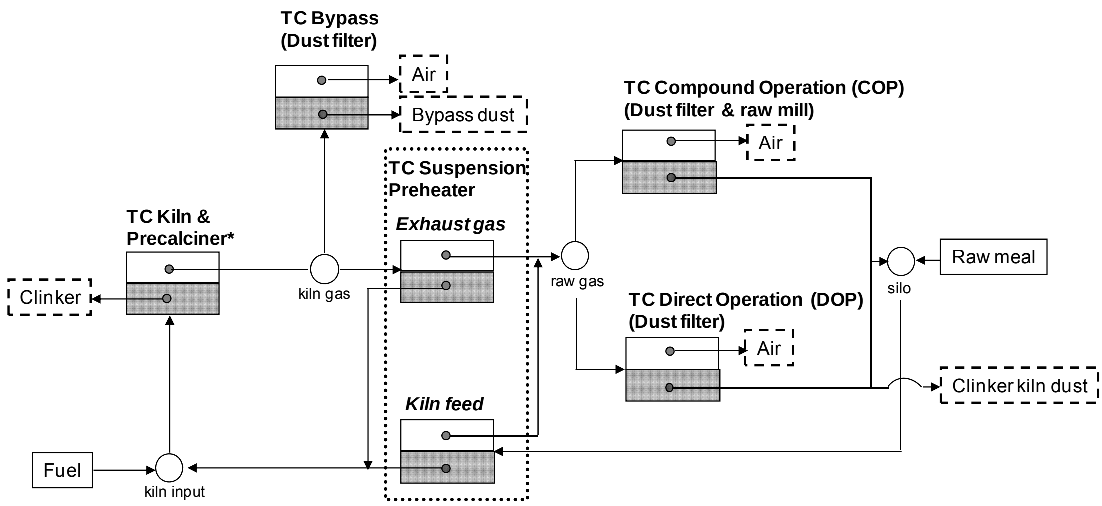
[d]Sewage sludge can be fired dewatered (ca. 30% dry substance, DS) or dried (ca. 92% DS). It is typically dewatered and dried at the wastewater-treatment plant before the transportation to the cement plant. Average electricity and heat consumption per ton of dried sewage sludge for dewatering (from 5% to 30% DS) and for drying (from 30% to 92% DS) is 243 kWh_e and 6265 MJ heat, respectively (*1*).

ANNEX 4: LOCATION OF USE OF TRANSFER COEFFICIENTS (TC) FOR DIFFERENT KILN TYPES AND DIFFERENT OUTPUTS FROM EACH PROCESS COMPONENT

Sets of transfer coefficients	Kiln / precalciner		Preheater (exhaust gas)		Preheater (kiln feed)		Bypass		Compound operation		Direct operation	
Output	Clinker	Kiln gas	Raw meal	Raw gas	Raw meal	Raw gas	Dust	Clean gas	Dust & raw meal	Clean gas	Dust (CKD)	Clean gas
Kiln type												
Precalciner	√	√	√	√	√	√	√	√	√	√	√	√
Suspension Preheater	√	√	√	√	√	√	√	√	√	√	√	√
Lepol	√	√	√	√	√	√	-	-	-	-	√	√
Long dry	√	√	-	-	-	-	-	-	√	√	√	√
Long wet	√	√	-	-	-	-	-	-	-	-	√	√

ANNEX 5: MASS FLOW SYSTEM OF KILN TYPES

Precalciner kiln system



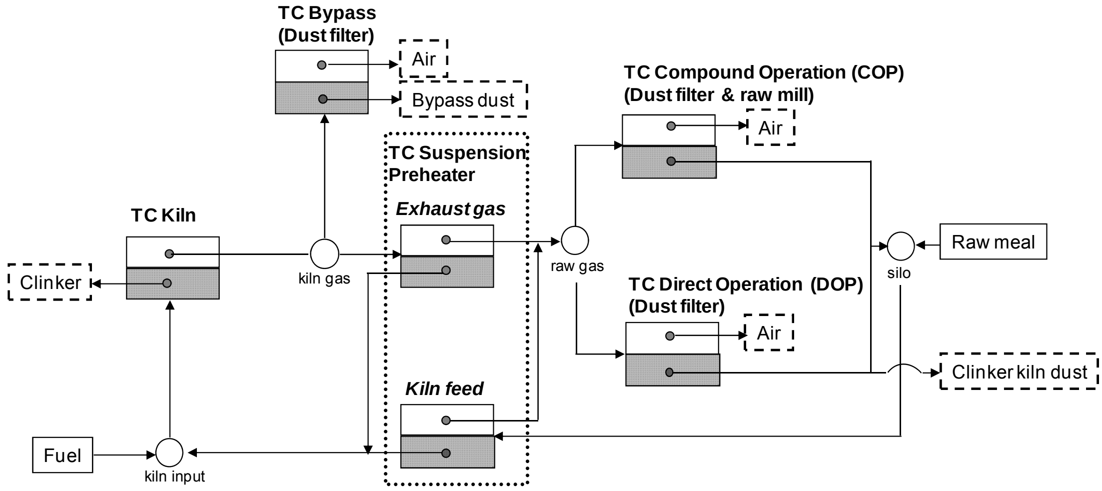
*The mass flow model does not differentiate between the separate firing systems of the main burner and the precalciner

Set of transfer coefficients (TC) for elements to model process compartments:

a not retained (kiln gas, raw gas, clean gas to air)

b retained (clinker, raw meal, clinker kiln dust, bypass dust) = (1-a)

Suspension preheater kiln system

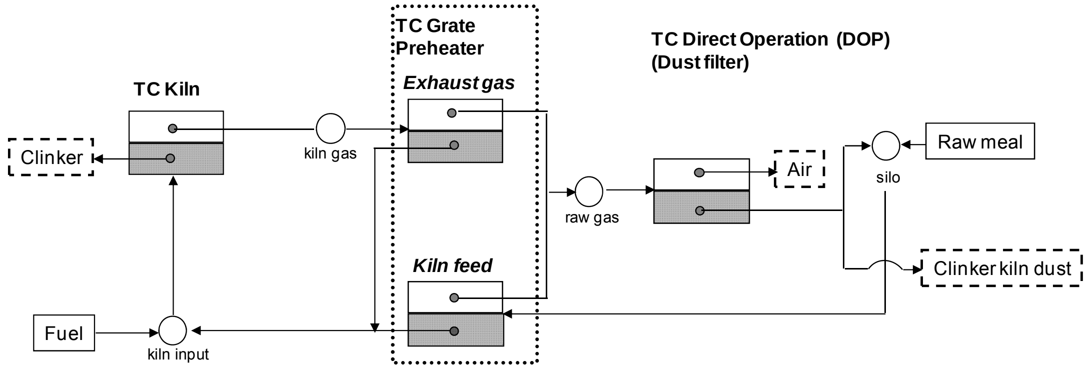


Set of transfer coefficients (TC) for elements to model process compartments:

a not retained (kiln gas, raw gas, clean gas to air)

b retained (clinker, raw meal, clinker kiln dust, bypass dust) = (1-a)

Lepol kiln system

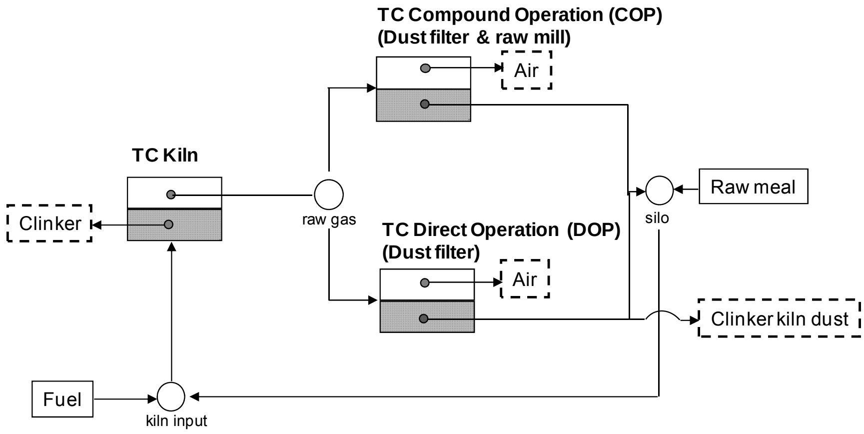


Set of transfer coefficients (TC) for elements to model process compartments:

a not retained (kiln gas, raw gas, clean gas to air)

b retained (clinker, raw meal, clinker kiln dust, bypass dust) = (1-a)

Long dry kiln system

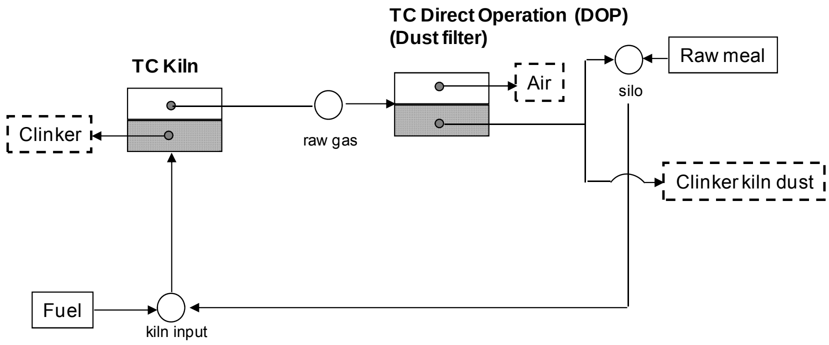


Set of transfer coefficients (TC) for elements to model process compartments:

a not retained (kiln gas, raw gas, clean gas to air)

b retained (clinker, raw meal, clinker kiln dust, bypass dust) = (1-a)

Long wet kiln system



Set of transfer coefficients (TC) for elements to model process compartments:

a not retained (kiln gas, raw gas, clean gas to air)

b retained (clinker, raw meal, clinker kiln dust, bypass dust) = (1-a)

Input:

Element in fuel and raw material mix

$$M_{e,\ fuel} = \sum_{i=1}^{n} l_i * x_{e,\ i}$$

$$M_{e,\ \text{raw material}} = \sum_{j=1}^{n} l_j * x_{e,\ j}$$

Intermediate compartments:

Kiln input

$$M_{e,\ \text{kiln input}} = M_{e,\ \text{fuel}} + M_{e,\ \text{silo}} * tc_{e,\ \text{Preheater-kilnfeed,retained}} + M_{e,\ \text{kiln gas}} * (1 - x_{\text{Bypass}}) * tc_{e,\ \text{Preheater-exhaustgas,retained}}$$

Kiln gas

$$M_{e,\ \text{kiln gas}} = M_{e,\ \text{kiln input}} * tc_{e,\ \text{kiln,notretained}}$$

Raw gas

$$M_{e,\ \text{raw gas}} = M_{e,\ \text{kiln gas}} * (1 - x_{\text{Bypass}}) * tc_{e,\ \text{Preheater-exhaust gas,notretained}} + M_{e,\ silo} * tc_{e,\ \text{Preheater-kiln feed,notretained}}$$

Silo

$$M_{e,\ \text{silo}} = M_{e,\ \text{raw material}} + M_{e,\ \text{raw gas}} * (1 - x_{\text{CKD}}) * ((1 - x_{\text{COP}}) * tc_{e,\ \text{DOP,retained}} + x_{\text{COP}} * tc_{e,\text{COP,retained}})$$

Output:

Clinker kiln dust

$$M_{e,\ \text{clinker kiln dust}} = M_{e,\ \text{raw gas}} * x_{\text{CDK}} * ((1 - x_{\text{COP}}) * tc_{e,\ \text{DOP,retained}} + x_{\text{COP}} * tc_{e,\ \text{COP,retained}})$$

Clinker

$$M_{e,\ clinker} = M_{e,\ \text{kiln input}} * tc_{e,\ \text{kiln,retained}}$$

Bypass dust

$$M_{e,\ \text{bypass dust}} = M_{e,\ \text{kiln gas}} * x_{\text{Bypass}} * tc_{e,\ \text{Bypass, retained}}$$

Air emissions from bypass operation

$$M_{e,\ \text{air (bypass)}} = M_{e,\ \text{kiln gas}} * x_{\text{Bypass}} * tc_{e,\text{Bypass,notretained}}$$

Air emissions from direct operation

$$M_{e,\ \text{air (direct operation)}} = M_{e,\ \text{raw gas}} * (1 - x_{\text{COP}}) * tc_{e,\text{DOP,notretained}}$$

Air emissions from compound operation

$$M_{e,\ \text{air (compound operation)}} = M_{e,\ \text{raw gas}} * x_{\text{COP}} * tc_{e,\text{COP,notretained}}$$

Variable	*Description*	*Unit*
I_i	Amount of fuel i in fuel mix	kg
I_j	Amount of raw material j in raw material mix	kg
$M_{e,\ fuel}$	Mass of element e in fuel mix	kg
$M_{e,\ raw\ material}$	Mass of element e in raw material mix	kg
$M_{e,\ kin\ input}$	Mass of element e in kiln input	kg
$M_{e,\ kiln\ gas}$	Mass of element e in kiln gas	kg
$M_{e,\ raw\ gas}$	Mass of element e in raw gas	kg
$M_{e,\ silo}$	Mass of element e in silo	kg
$M_{e,\ clinker}$	Mass of element e in clinker	kg
$M_{e,\ bypass\ dust}$	Mass of element e in bypass dust	kg
$M_{e,\ clinker\ kiln\ dust}$	Mass of element e in clinker kiln dust	kg
$M_{e,\ air\ (bypass)}$	Mass of element e in air from bypass operation	kg
$M_{e,\ air\ (direct\ operation)}$	Mass of element e in air from direct operation	kg
$M_{e,\ air\ (compound\ operation)}$	Mass of element e in air from compound operation	kg
$tc_{e,\ kiln,notretained}$	Transfer coefficient of element e in kiln to kiln gas	-
$tc_{e,\ kiln,retained}$	Transfer coefficient of element e in kiln to clinker	-
$tc_{e,\ bypass,notretained}$	Transfer coefficient of element e in bypass dust filter to clean air	-
$tc_{e,\ bypass,retained}$	Transfer coefficient of element e in bypass dust filter to bypass filter dust	-
$tc_{e,\ preheater\text{-}exhaust\ gas,notretained}$	Transfer coefficient of element e in preheater gas to raw gas	-
$tc_{e,\ preheater\text{-}exhaust\ gas,retained}$	Transfer coefficient of element e in preheater gas to suspended raw meal	-
$tc_{e,\ preheater\text{-}kiln\ feed,notretained}$	Transfer coefficient of element e in preheater kiln feed to raw gas	-
$tc_{e,\ preheater\text{-}kiln\ feed,retained}$	Transfer coefficient of element e in preheater kiln feed to susp. raw meal	-
$tc_{e,\ COP,notretained}$	Transfer coefficient of element e in dust filter (COP) to clean gas	-
$tc_{e,\ COP,retained}$	Transfer coefficient of element e in dust filter (COP) to filter dust	-
$tc_{e,\ DOP,notretained}$	Transfer coefficient of element e in dust filter (DOP) to clean gas	-
$tc_{e,\ DOP,retained}$	Transfer coefficient of element e in dust filter (DOP) to filter dust	-
x_{bypass}	Fraction of kiln gas withdrawn by bypass	-
x_{CKD}	Fraction of direct operation filter dust not routed back to silo	-
x_{COP}	Compound operation rate	-
$x_{e,i}$	Weight fraction of element e in fuel i	-
$x_{e,j}$	Weight fraction of element e in raw material j	-

ANNEX 6: CALCULATION OF EXHAUST GAS VOLUME

Exhaust gas volume:

$$V_{feed} = (n_{c(org)} + n_{c(calcination)} + n_S + n_N/2) * V_m$$

$$V_{N,air} = (n_{c(org)} + n_S + n_H/4 - n_O/2) * (c_{N2,air}/c_{O2,air}) * V_m$$

$$V_{gas,dry,x\%O2} = (V_{feed} + V_{N,air}) * (1 + x\%/(21\% - x\%))$$

Variable	*Description*	*Unit*
$c_{O2,air}$	Oxygen content of air	%
$c_{N2,air}$	Nitrogen content of air	%
n_i	Moles of substance i in fuels and raw materials	mol
$C_{(org)}$	Organic carbon in fuels and raw materials	-
$C_{(calcination)}$	Inorganic carbon in fuels and raw materials ($CaCO_3$, $MgCO_3$)	-
H	Hydrogen in fuels and raw materials	-
O	Oxygen in fuels and raw materials	-
S	Sulfur in fuels and raw materials	-
N	Nitrogen in fuels and raw materials	-
V_{feed}	Gas volume resulting from oxidation and calcination of fuels and raw materials	m3
$V_{N,air}$	Volume of nitrogen in the mass of air used for oxidation and calcination of fuels and raw mat.	m3
V_m	Molar volume	m^3/mol
x	Oxygen content in exhaust gas	%

ANNEX 7: CHARACTERISTICS OF RESOURCES (CASE STUDY)

		Hard coal	Petcoke	Natural gas	RDF (prepared municipal waste)[a]	Prepared industrial waste[b]	Waste rubber	Sewage sludge (dry)	Tires, whole[c]	Waste solvents
	Unit	kg	kg	Nm3	kg	kg	kg	kg	kg	kg
Heating value										
NCV (Net calorific value)	MJ	29.40	32.22	34.32	16.81	16.67	27.12	9.03	25.00	21.70
CO_2 emission factor	*kg / GJ*	*96.0*	*92.8*	*56.1*	*83.0*	*83.0*	*85.0*	*110.0*	*85.0*	*80.5*
Fuel composition										
H_2O (as fired)	%	0.60	0.66	0.00	21.22	27.58	10.10	7.20	0.00	16.50
C org (TOC)	%	77.00	81.60	52.55	38.10	37.75	62.90	27.10	58.00	47.70
S	%	0.54	3.68	0.01	0.31	0.19	0.23	0.83	1.30	0.70
N	%	1.60	2.00	14.39	0.50	0.00	0.50	3.54	0.50	1.00
Cl	%	0.07	0.01	0.00	0.56	0.18	0.67	0.05	0.00	2.40
F	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	%	3.82	3.90	32.64	5.00	5.00	5.00	4.00	12.00	8.20
O	%	8.92	7.37	0.31	15.97	14.61	5.93	3.00	6.53	23.10
Ash (composition is shown below)	%	6.77	0.62	0.10	14.58	12.58	14.39	44.58	21.30	0.30
Calcination CO_2	*%*	*0.66*	*0.03*	*0.00*	*3.68*	*2.02*	*0.00*	*9.48*	*0.00*	*0.00*
Trace elements										
Cd	ppm	0.10	0.00	0.00	7.00	29.00	30.00	1.57	0.50	0.00
Hg	ppm	0.14	0.00	0.00	0.50	0.60	0.29	0.89	0.02	0.00
Tl	ppm	0.20	0.00	0.00	0.00	0.00	0.00	0.23	0.50	0.00
Sb	ppm	1.00	0.00	0.00	23.00	21.00	57.00	5.00	0.50	0.00
As	ppm	2.00	0.00	0.00	2.00	1.90	6.00	5.30	0.50	0.00
Pb	ppm	10.00	0.00	0.00	61.00	58.00	194.00	70.33	10.00	0.00
Cr	ppm	31.00	0.00	0.00	43.00	60.00	30.00	71.00	17.00	0.00
Co	ppm	7.00	0.00	0.00	10.00	5.70	0.00	7.33	22.00	4.00
Cu	ppm	10.00	0.00	0.00	68.00	247.00	107.00	358.33	151.00	6.00
Mn	ppm	60.00	0.00	0.00	74.00	94.00	33.00	321.00	534.00	0.00
Ni	ppm	19.00	300.00	0.00	17.00	19.30	7.00	33.67	30.00	5.00
V	ppm	29.00	1000.00	0.00	9.00	18.00	23.00	23.67	0.50	0.00
Sn	ppm	3.00	0.00	0.00	54.00	84.00	13.00	460.00	0.50	0.00
Zn	ppm	14.00	0.00	0.00	394.00	279.00	2328.00	867.67	2935.00	60.00
Ash composition (adds up to 100%), for ash content see above row "Ash"										
SiO_2	%	47.34	13.86	0.00	37.56	56.51	49.47	24.77	1.40	0.00
Al_2O_3	%	16.81	13.75	0.00	19.78	15.26	11.63	10.20	0.00	0.00
Fe_2O_3	%	19.15	65.42	0.00	6.72	8.16	8.90	16.94	96.15	100.00
CaO	%	6.56	3.54	0.00	26.43	15.28	24.32	24.77	0.00	0.00
MgO	%	4.25	1.36	0.00	4.13	3.69	0.00	1.67	0.00	0.00
SO_3	%	5.89	2.07	100.00	5.38	1.10	5.69	4.65	2.45	0.00
K_2O	%	0.00	0.00	0.00	0.00	0.00	0.00	1.16	0.00	0.00
Na_2O	%	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00
P_2O_5	%	0.00	0.00	0.00	0.00	0.00	0.00	15.52	0.00	0.00
Further characteristics										
Biogenic C / Total C	%	0%	0%	0%	15%	40%	0%	100%	27%	0%

[a]RDF (prepared municipal solid waste): Mix of 75% plastics, 10% rubber, 10% textile, 5% wood

[b]Prepared industrial waste: Mix of 40% saw dust, 20% sludge (from refinery), 40% shredder residue (from automotive industry)

[c]Tires, whole: The average content of biogenic carbon in passenger car and truck tires is 23% and 31%, respectively (due to natural rubber contents) (*2*). Regulatory specification for emissions trading in Germany, Austria and Switzerland is 27% biogenic C for waste tires (regulations for the accounting of biogenic C in tires may differ in other countries).

The chemical composition and net calorific values of the fuels and wastes are from the environmental report of the case study plant, with the exception of the waste solvent (*3*) and the heavy metal contents of hard coal, petcoke and natural gas (*4*). The net calorific values of waste rubber and tires reported at the case study plant are lower than commonly found in literature (approximately 33 MJ/kg for waste rubber (e.g. (*5*)) and 28-37 MJ/kg for tires (e.g. (*6*)), probably due to high contents of water and inert materials.

The carbon content (of all fuels except the waste solvent (*3*)) has been calculated in order to obtain the CO_2 emission factors provided by WBCSD Cement Sustainability Initiative (*7*). The oxygen content has been adjusted that the total mass sums up to 100%.

		Limestone	Clay	Fe-corrective (iron ore)	Blast furnace slag
	Unit	**kg**	**kg**	**kg**	**kg**
Main elements					
H_2O (in kiln feed)	%	1.00	1.00	1.00	1.00
TOC (C org)	%	0.20	1.50	0.20	0.20
Cl	%	0.00	0.01	0.01	0.02
SiO_2	%	1.09	62.97	3.79	37.49
Al_2O_3	%	0.55	14.60	3.40	13.95
Fe_2O_3	%	0.36	5.15	72.00	0.80
CaO	%	53.40	6.00	7.94	39.39
MgO	%	1.30	2.29	4.20	5.94
SO_3	%	0.05	0.79	0.42	0.09
K_2O	%	0.10	0.70	0.41	0.61
Na_2O	%	0.02	0.20	0.16	0.48
P_2O_5	%	0.00	0.00	0.07	0.00
Calcination CO2	*%*	*41.91*	*4.71*	*6.23*	*0.00*
Trace elements					
Cd	ppm	0.10	0.37	0.83	0.00
Hg	ppm	0.01	0.02	0.05	0.00
Tl	ppm	0.14	0.09	74.89	0.00
Sb	ppm	1.00	0.80	0.00	0.00
As	ppm	0.70	0.70	9.10	80.00
Pb	ppm	0.20	10.00	6.55	50.00
Cr	ppm	14.80	71.00	41.65	28.40
Co	ppm	1.00	21.00	0.00	8.42
Cu	ppm	0.50	14.00	0.00	42.00
Mn	ppm	204.00	414.00	0.00	0.00
Ni	ppm	1.00	33.00	2.98	24.27
V	ppm	1.10	116.00	0.00	22.56
Sn	ppm	1.00	4.20	0.00	6.90
Zn	ppm	15.00	87.70	31.61	5.84
Further characteristics					
Pyritic (volatile) S / total S	%	5%	5%	5%	5%
Carbonated CaO & MgO	%	100%	100%	100%	0%

The chemical composition (main elements) of limestone, clay and iron ore is from the environmental report of the case study plant. Chemical composition of blast furnace slag and the heavy metals in limestone, clay and iron ore are from Holcim HGRS (*4*). Mineral composition has been amended that the total mass sums up to 100%. For raw materials which have not already been calcined (limestone, clay, iron ore), 100% carbonation of CaO and MgO is assumed. The actual carbonation rate may be lower as these oxides can be present in silicate phases. The organic carbon in raw materials is of fossil origin.

ANNEX 8: ELEMENT TRANSFER COEFFICIENTS (CASE STUDY)

		Transfer coefficients											
		Kiln, Precalciner & Preheater						DeDusting devices					
		Kiln / Precalciner		Preheater (raw gas leaving kiln)		Preheater (raw meal entering preheater)		Bypass		Compound operation		Direct operation	
		clinker	raw gas	suspended raw meal	raw gas	suspended raw meal	raw gas	dust (bypass dust)	clean gas	dust & raw material	clean gas	dust (CKD)	clean gas
Main elements													
S (in fuel)	%	1.000%	**99%**	99.000%	**1%**	-*	**-***	60.000%	**40%**	60.000%	**40%**	0.000%	**100%**
S pyritic (in raw material)	%	1.000%	**99%**	99.000%	**1%**	30.000%	**70%**	60.000%	**40%**	60.000%	**40%**	0.000%	**100%**
S non-pyritic (in raw material)	%	45.000%	**55%**	99.000%	**1%**	100.000%	**0%**	60.000%	**40%**	60.000%	**40%**	0.000%	**100%**
Trace elements													
Cd	%	61.900%	**38.100%**	0.000%	**100.000%**	80.000%	**20.000%**	99.812%	**0.188%**	99.954%	**0.046%**	99.812%	**0.188%**
Hg	%	0.000%	**100.000%**	0.000%	**100.000%**	5.000%	**95.000%**	80.000%	**20.000%**	84.000%	**16.000%**	80.000%	**20.000%**
Tl	%	2.100%	**97.900%**	0.000%	**100.000%**	50.000%	**50.000%**	99.873%	**0.127%**	99.928%	**0.072%**	99.873%	**0.127%**
Sb	%	88.000%	**12.000%**	0.000%	**100.000%**	100.000%	**0.000%**	99.812%	**0.188%**	99.954%	**0.046%**	99.812%	**0.188%**
As	%	88.000%	**12.000%**	0.000%	**100.000%**	100.000%	**0.000%**	99.812%	**0.188%**	99.954%	**0.046%**	99.812%	**0.188%**
Pb	%	91.870%	**8.130%**	0.000%	**100.000%**	100.000%	**0.000%**	99.810%	**0.190%**	99.943%	**0.057%**	99.810%	**0.190%**
Cr	%	93.000%	**7.000%**	0.000%	**100.000%**	100.000%	**0.000%**	99.857%	**0.143%**	99.979%	**0.021%**	99.857%	**0.143%**
Co	%	97.060%	**2.940%**	0.000%	**100.000%**	100.000%	**0.000%**	99.857%	**0.143%**	99.979%	**0.021%**	99.857%	**0.143%**
Cu	%	97.060%	**2.940%**	0.000%	**100.000%**	100.000%	**0.000%**	99.857%	**0.143%**	99.979%	**0.021%**	99.857%	**0.143%**
Mn	%	97.060%	**2.940%**	0.000%	**100.000%**	100.000%	**0.000%**	99.857%	**0.143%**	99.979%	**0.021%**	99.857%	**0.143%**
Ni	%	97.060%	**2.940%**	0.000%	**100.000%**	100.000%	**0.000%**	99.857%	**0.143%**	99.979%	**0.021%**	99.857%	**0.143%**
V	%	97.060%	**2.940%**	0.000%	**100.000%**	100.000%	**0.000%**	99.857%	**0.143%**	99.979%	**0.021%**	99.857%	**0.143%**
Sn	%	99.443%	**0.557%**	0.000%	**100.000%**	100.000%	**0.000%**	99.609%	**0.391%**	99.921%	**0.079%**	99.609%	**0.391%**
Zn	%	99.443%	**0.557%**	0.000%	**100.000%**	100.000%	**0.000%**	99.609%	**0.391%**	99.921%	**0.079%**	99.609%	**0.391%**

*Fuels are not fed via the preheater, but directly to the kiln or precalciner

The transfer coefficients applied in the case study are based on studies on the behavior of heavy metals in precalciner / suspension preheater kiln systems (*8*). For the specific case of thallium, the transfer coefficients were calculated on the basis of regulatory emission limits (*9*). Information on the behavior of sulfur is from Holcim HGRS (*4*).

ANNEX 9: PREDICTED VS. MEASURED OUTCOME OF THE CASE STUDY PLANT: LIFE CYCLE INVENTORY (LCI) AND LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Model input: Plant layout, Fuels (% heat), Raw materials (% weight), Amount of Clinker kiln dust, Chemical composition of resources, Preparation of resources, Region

Model input

Model input

Plant layout	
Kiln type	Precalciner
COP	90%
NO_x treatment	-
SO_2 treatment	-
Dust filter	Fabric filter
Clinker kiln dust removal	0%
Bypass	-
Fuels	***Heat (%)***
Coal	50.00
Petcoke	22.40
Natural gas	0.80
Prepared industrial waste	10.9
RDF (prepared municipal solid waste)	13.00
Waste rubber	0.70
Tires, whole	2.20
Raw materials	***Weight (%)***
Limestone	78.48
Clay	20.35
Iron ore	1.17
Resource characteristics and preparation	
All resources	see Supporting Information S3, S7
Region	
Regional LCA data for supply chains (only electricity and hard coal)	Eastern Europe

Model output: Heat requirement, Electricity requirement, Flue gas amount, LCI at plant level, LCIA of supply chains (resources and operating materials), LCIA of cradle-to-gate clinker production

The predicted outcome in the below table is a result of the model calculations. The measured outcome refers to reported data measured at the case study plant, except for the flue gas volume, which was calculated with the formula provided in S6. The LCIA of the supply chains is calculated from ecoinvent data (*10*).

Model output I: Life Cycle Inventory (LCI) of case study and comparison to reported/measured data from the case study plant (gate-to-gate, i.e. at plant level, excl. supply chains)

Model output

	Unit	predicted	measured	abs. error	rel. error (%)
Operation					
Heat requirement	MJ / t clinker	3295.00	3348.00	-53.00	-1.6%
Electricity (total)	kWh / t clinker	76.50	63.00	13.50	21.4%
Flue gas volume	Nm3 / t clinker	2085.00	2114.00	-29.00	-1.4%
Emissions to air					
CO_2	kg / t clinker	828.00	833.00	-5.00	-0.6%
NO_x	mg / Nm^3	679.00	510.00	169.00	33.1%
SO_2	mg / Nm^3	42.72	37.00	5.72	15.5%
Dust	mg / Nm^3	13.65	4.00	9.65	241.3%
CO	mg / Nm^3	1000.00	not reported	-	-
VOC	mg / Nm^3	40.00	24.00	16.00	66.7%
Benzene	mg / Nm^3	1.00	0.02	0.99	6566.7%
PCDD/F	ng TEQ/ Nm^3	1.0E-01	4.0E-03	0.0960	2400.0%
HCl	mg / Nm^3	2.59	4.40	-1.81	-41.1%
HF	mg / Nm^3	0.00	not reported	-	-
NH_3	mg / Nm^3	10.00	9.20	0.80	8.7%
Cd	mg / Nm^3	2.6E-04	*	-	-
Hg	mg / Nm^3	2.3E-02	3.8E-02	-1.5E-02	-39.1%
Tl	mg / Nm^3	5.0E-02	*	-	-
Sb	mg / Nm^3	1.0E-04	6.0E-03	-5.9E-03	-98.3%
As	mg / Nm^3	5.6E-05	*	-	-
Pb	mg / Nm^3	2.1E-04	2.0E-02	-2.0E-02	-98.9%
Cr	mg / Nm^3	5.4E-04	*	-	-
Co	mg / Nm^3	4.2E-05	*	-	-
Cu	mg / Nm^3	6.4E-05	*	-	-
Mn	mg / Nm^3	1.9E-03	9.3E-03	-7.4E-03	-80.1%
Ni	mg / Nm^3	9.9E-05	*	-	-
V	mg / Nm^3	3.0E-04	*	-	-
Sn	mg / Nm^3	1.7E-05	not reported	-	-
Zn	mg / Nm^3	2.2E-04	not reported	-	-
Resources					
Hard coal	kg / t clinker	56.00	56.91	-0.91	-1.6%
Petcoke	kg / t clinker	22.90	23.27	-0.37	-1.6%
Natural gas	kg / t clinker	0.80	0.81	-0.01	-1.6%
RDF	kg / t clinker	21.60	21.95	-0.35	-1.6%
Prep. industrial waste	kg / t clinker	25.50	25.91	-0.41	-1.6%
Waste rubber	kg / t clinker	0.80	0.81	-0.01	-1.6%
Tires	kg / t clinker	2.90	2.95	-0.05	-1.6%
Limestone	kg / t clinker	1197.50	1197.30	0.20	0.0%
Clay	kg / t clinker	311.50	310.90	0.60	0.2%
Iron ore	kg / t clinker	17.90	17.90	0.00	0.0%

* below detection limit

Detection limits (mg/m3): Cd: 0.002; Tl: 0.004; As, V: 0.005; Ni: 0.006; Cu: 0.008; Cr, Co: 0.01

Model output II: Life Cycle Impact Assessment (LCIA) of case study (cradle-to-gate, i.e. plant incl. supply chains of resources and operating materials)

	IPCC 2001 Climate change kg CO_2-Eq.		CExD Non-renew. resources MJ-Equivalents		Eco-indicator'99 (H,A) Ecosystem quality points		Eco-indicator'99 (H,A) Human health points		Eco-indicator'99 (H,A) Resources points		Eco-indicator'99 (H,A) Total points	
	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured
CO2	828	833	-	-	-	-	4.52	4.54	-	-	4.52	4.54
NOx	-	-	-	-	0.63	0.48	3.26	2.48	-	-	3.89	2.96
SO2	-	-	-	-	0.01	0.01	0.13	0.11	-	-	0.13	0.12
VOC, Benzene, CO	2	1	-	-	0.00	0.00	0.03	0.01	-	-	0.03	0.01
PCDD/F	-	-	-	-	0.00	0.00	0.00	0.00	-	-	0.00	0.00
Heavy metals	-	-	-	-	0.00	0.01	0.00	0.00	-	-	0.01	0.01
Dust	-	-	-	-	-	-	0.44	0.08	-	-	0.44	0.08
NH3, HCl, HF	-	-	-	-	0.03	-	0.05	0.04	-	-	0.07	0.07
Resources supply chain	42	43	3516	3564	0.34	0.35	2.41	2.43	5.43	5.50	8.19	8.27
Operating mat. supply chain	72	60	1034	863	0.17	0.15	1.67	1.40	0.53	0.46	2.38	2.01
LCIA score	**944**	**937**	**4550**	**4427**	**1.18**	**1.00**	**12.50**	**11.09**	**5.96**	**5.95**	**19.65**	**18.07**
Predicted/Measured	***101%***		***103%***		***118%***		***113%***		***100%***		***109%***	

	CML 2001 Acidification pot. kg SO_2-Eq		CML 2001 Eutrophication pot. kg PO_4-Eq		CML 2001 Human toxicity kg 1,4-DCB-Eq		CML 2001 Summer smog kg formed ozone		Ecological footprint Total m^2a		Ecological scarcity Total points	
	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured
CO2	-	-	-	-	-	-	-	-	2214	2225	256828	258230
NOx	0.71	0.54	0.18	0.14	1.70	1.29	-	-	-	-	63707	48516
SO2	0.11	0.09	-	-	0.01	0.01	-	-	-	-	2690	2347
VOC, Benzene, CO	-	-	-	-	3.96	0.06	0.001	0.000	-	-	8515	481
PCDD/F	-	-	-	-	0.00	0.02	-	-	-	-	12	482
Heavy metals	-	-	-	-	1.81	0.03	-	-	-	-	10371	18011
Dust	-	-	-	-	0.02	0.01	-	-	-	-	4379	1268
NH3, HCl, HF	0.03	0.03	0.01	0.01	0.00	0.01	-	-	-	-	1343	1363
Resources supply chain	0.34	0.35	0.04	0.04	9.76	9.87	0.012	0.012	101	102	55314	55850
Operating mat. supply chain	0.36	0.30	0.02	0.01	11.79	10.72	0.003	0.003	223	186	46569	39253
LCIA score	**1.55**	**1.31**	**0.25**	**0.20**	**29.06**	**22.01**	**0.016**	**0.015**	**2538**	**2513**	**449728**	**425801**
Predicted/Measured	***118%***		***123%***		***132%***		***105%***		***101%***		***106%***	

Information on the applied LCIA methods is provided in (*11*)

ANNEX 10: LCI AND LCIA OF CO-PROCESSING TIRES, PREPARED INDUSTRIAL WASTE, SEWAGE SLUDGE AND BLAST FURNACE SLAG

Life Cycle Inventory (LCI) of co-processing 20 kg tires, prepared industrial waste, sewage sludge and blast furnace slag (the base case is the case study in S9) (gate-to-gate, i.e. excl. supply chains)

		Base case	Tires, whole	Prepared industrial waste	Sewage sludge	Blast furnce slag
		-	+ 20 kg	+ 20 kg	+ 20 kg	+ 20 kg
Process / Operation						
Heat requirement	MJ	3295	3298	3309	3307	3295
Exaust gas volume	Nm3	2085	2131	2085	2125	2079
Emissions						
CO_2 traditional fuels	kg	254	206	223	238	254
CO_2 wastes	kg	55	86	71	55	55
CO_2 calcination	kg	520	520	520	519	513
CO_2 total	kg	828	812	814	811	821
NO_x	kg	1.5	1.5	1.5	1.5	1.5
SO_2	kg	0.1	0.1	0.1	0.1	0.1
Dust	kg	0.02	0.02	0.02	0.02	0.02
CO	kg	2.1	2.1	2.1	2.1	2.1
VOC	kg	0.08	0.09	0.08	0.09	0.08
Benzene	kg	0.002	0.002	0.002	0.002	0.002
PCDD/F (TEQ)	kg	2.1E-10	2.1E-10	2.1E-10	2.1E-10	2.1E-10
NH_3	kg	0.02	0.02	0.02	0.02	0.02
HCl	kg	0.01	0.01	0.01	0.01	0.01
HF	kg	0.00	0.00	0.00	0.00	0.00
Cd	kg	5.4E-07	5.4E-07	8.1E-07	5.5E-07	5.4E-07
Hg	kg	4.8E-05	4.6E-05	5.9E-05	6.5E-05	4.8E-05
Tl	kg	1.1E-04	1.0E-04	1.0E-04	9.6E-05	1.0E-04
Sb	kg	2.1E-07	2.1E-07	2.5E-07	2.2E-07	2.1E-07
As	kg	1.2E-07	1.1E-07	1.2E-07	1.2E-07	2.5E-07
Pb	kg	4.4E-07	4.4E-07	5.0E-07	5.2E-07	4.9E-07
Cr	kg	1.1E-06	1.1E-06	1.1E-06	1.1E-06	1.1E-06
Co	kg	8.7E-08	9.0E-08	8.7E-08	8.7E-08	8.6E-08
Cu	kg	1.3E-07	1.6E-07	1.8E-07	2.0E-07	1.4E-07
Mn	kg	3.9E-06	4.0E-06	3.9E-06	3.9E-06	3.8E-06
Ni	kg	2.1E-07	2.1E-07	2.1E-07	2.1E-07	2.1E-07
V	kg	6.3E-07	6.3E-07	6.3E-07	6.3E-07	6.2E-07
Sn	kg	3.6E-08	3.6E-08	4.6E-08	9.3E-08	3.7E-08
Zn	kg	4.5E-07	8.1E-07	4.8E-07	5.5E-07	4.4E-07
Resources						
Tires, whole	kg	-	20	-	-	-
Prep. industrial waste	kg	-	-	20	-	-
Sewage sludge	kg	-	-	-	20	-
Blast furnace slag	kg	-	-	-	-	20
Hard coal	kg	-	-17	-11	-6	0
Limestone	kg	-	2	0	-5	-14
Clay	kg	-	2	-2	-4	-12
Iron ore	kg	-	-6	0	-2	0

Life Cycle Impact Assessment (LCIA) of co-processing 20 kg tires, prepared industrial waste, sewage sludge and blast furnace slag (the base case is the case study in S9) (cradle-to-gate, i.e. plant incl. supply chains of resources and operating materials)

	IPCC 2001 **Climate change** kg CO_2-Eq. Base case	Tires, whole	Prepared industrial waste	Sewage sludge (dried)	Blast furnce slag
Emissions at plant					
CO_2	828	812	814	811	821
NO_x	-	-	-	-	-
SO_2	-	-	-	-	-
VOC, Benzene, CO	2	2	2	2	2
PCDD/F	-	-	-	-	-
Heavy metals	-	-	-	-	-
Dust	-	-	-	-	-
NH_3, HCl, HF	-	-	-	-	-
Supply chains					
Resources	42	37	40	56	42
Operating materials	72	71	72	72	72
LCIA score	**944**	**922**	**928**	**941**	**937**

	CExD **Non-renew. resources** MJ-Equivalents Base case	Tires, whole	Prepared industrial waste	Sewage sludge (dried)	Blast furnce slag
Emissions at plant					
CO_2	-	-	-	-	-
NO_x	-	-	-	-	-
SO_2	-	-	-	-	-
VOC, Benzene, CO	-	-	-	-	-
PCDD/F	-	-	-	-	-
Heavy metals	-	-	-	-	-
Dust	-	-	-	-	-
NH_3, HCl, HF	-	-	-	-	-
Supply chains					
Resources	3516	3012	3217	3487	3510
Operating materials	1034	1024	1027	1029	1032
LCIA score	**4550**	**4036**	**4245**	**4516**	**4542**

	Eco-indicator'99 (H,A) Total points				
	Base case	Tires, whole	Prepared industrial waste	Sewage sludge (dried)	Blast furnce slag
Emissions at plant					
CO_2	4.52	4.43	4.44	4.43	4.48
NO_x	3.89	3.89	3.89	3.89	3.89
SO_2	0.13	0.13	0.13	0.13	0.13
VOC, Benzene, CO	0.03	0.03	0.03	0.03	0.03
PCDD/F	0.00	0.00	0.00	0.00	0.00
Heavy metals	0.01	0.01	0.01	0.01	0.01
Dust	0.44	0.44	0.44	0.44	0.44
NH_3, HCl, HF	0.07	0.07	0.07	0.07	0.07
Supply chains					
Resources	8.19	7.83	8.04	8.86	8.18
Operating materials	2.38	2.36	2.36	2.37	2.37
LCIA score	**19.65**	**19.19**	**19.41**	**20.23**	**19.60**

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