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WILCI: A LCA TOOL DEDICATED TO MSW INCINERATION IN FRANCE

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SUMMARY: Life Cycle Assessment (LCA) has been increasingly used in the last decades to evaluate the global environmental performance of waste treatment options. This is in particular the case considering incineration that is the major treatment route for Municipal Solid Waste (MSW) in France (28% of French MSW are incinerated, in 126 MSW incineration plants; ADEME, 2015). In this context, this article describes a new Excel-tool, WILCI (for Waste Incineration Life Cycle Inventory tool), dedicated to the LCA of MSW incineration in the French situation. In view of the similarities between French and other European MSW management systems, it can be considered a robust tool to perform the LCA of MSW incineration in many European countries. An overview is here given respectively regarding the kind of case studies that WILCI offers to model, the parameters that can be modified by users and the kind of results calculated. WILCI enables users to build a Life Cycle Inventory relative to the incineration of a given amount of MSW, considering technologies and performances (in terms of emissions, energy, etc.) representative of the specific system under study. Users have the possibility to define several parameters, including in particular: the type of waste that is treated (by waste category and by chemical element), the Air Pollution Control (APC) technologies implemented (e.g. acid gas treatment, DeNOx), the corresponding level of emissions, the level of energy recovery and delivery to the grid, the consumption of reagents, and the fate of solid residues downstream the incinerator. Considering each of these parameters, default values, for most of them based on datasets collected with respect to 90 French MSW incineration plants considering the period 2012-2015, and therefore representative of average MSW incineration in France, are pre-implemented in WILCI and can be used as such by LCA modellers. Given these user-modifiable parameters, and their corresponding defaults values, this tool is well adapted to perform the LCA of several types of case studies, including: i) the average MSW incineration system in France, ii) the incineration of average MSW, in plants equipped with a given APC technology, and iii) the incineration of specific waste categories (e.g. paper). Two types of outputs are calculated from WILCI: on the one hand, elementary flows directly emitted from the incinerator to the environment and, on the other hand, energy, reagents and solid residues that require an additional modelling with dedicated databases. WILCI was built in line with the ecoinvent approach for Life Cycle Inventories relative to MSW incineration, so that the calculated outputs are “ecoinvent-compliant”. In particular, data uncertainty was quantified in line with the uncertainty approach used in ecoinvent. WILCI is free of charge and can be obtained upon request to the developing team.

1. INTRODUCTION

Life Cycle Assessment (LCA) has been increasingly used in the last decades to evaluate the global environmental performance of waste treatment options. This is in particular the case considering incineration that is the major treatment route for Municipal Solid Waste (MSW) in France (28% of French MSW are incinerated, in 126 MSW incineration plants; ADEME, 2015). LCA studies generally confirm the waste hierarchy: from an environmental point of view, recycling performs better than thermal treatment, that performs better than landfilling (Laurent et al., 2014; Astrup et al., 2015). However, MSW incineration environmental performances are dependent on the specific features of each incineration plant under study (Beylot and Villeneuve, 2013).

In this context, this article aims at describing a new tool, WILCI (for Waste Incineration Life Cycle Inventory tool) developed with Microsoft Excel 2010 and dedicated to the LCA of MSW incineration in the French situation. WILCI has been designed so that users may perform the LCA of several types of case studies, including: i) the average MSW incineration system in France, ii) the incineration of average MSW, in plants equipped with a given Air Pollution Control (APC) technology, and iii) the incineration of specific waste categories (e.g. paper). WILCI is pre-filled with default data primarily representative of the French MSW incineration sector, which may be changed by users if necessary to better represent their system under study.

In a first section, this article presents an overview of WILCI, in terms of objectives, scope and worksheets. Then, the article goes deeper in the description, on the one hand of user-modifiable worksheets, which enable input data definition (section 3), and on the other hand of the main calculation operations, implemented in the tool to derive the resulting Life Cycle Inventory (LCI; section 4). In this article, the focus is on key parameters, default values and calculation operations. Accordingly, some parameters, data and calculation operations are not detailed here. Yet, a broader description is available in WILCI worksheets and WILCI user-guide, where parameters, default values and calculations are thoroughly reported in order to ensure transparency. Finally, the last section of this article describes the worksheet that reports the resulting LCI, and its potential for export to Simapro v8 for subsequent Life Cycle Impact Assessment (LCIA).

2. TOOL OVERVIEW

WILCI enables users to calculate the LCI relative to the thermal treatment of a given quantity of MSW. The system boundaries include incineration direct emissions to air and water, production and consumption of ancillary materials, solid residues (bottom ashes, fly ashes and scrubber sludge) transport and treatment, energy recovery as heat and electricity, steel and aluminium scraps recovery, infrastructures and maintenance. On the contrary, waste collection and transport to the incinerator, services associated with the incineration (for example commercial services) and plant decommissioning are not considered. The main inputs to the model implemented in WILCI, and the main outputs (elements of the resulting LCI), are depicted in Figure 1.

WILCI is mainly made of three types of worksheets (Table 1). Firstly, user-modifiable worksheets enable users to define the parameters that characterize their system, in terms of waste composition, APC techniques and associated emissions, product flows (reagents, metal scraps recovery and energy), management of output APC residues and bottom ashes, and data uncertainties. Default data are pre-implemented in these worksheets, in most cases derived from recently collected data relative to the French MSW incineration sector.

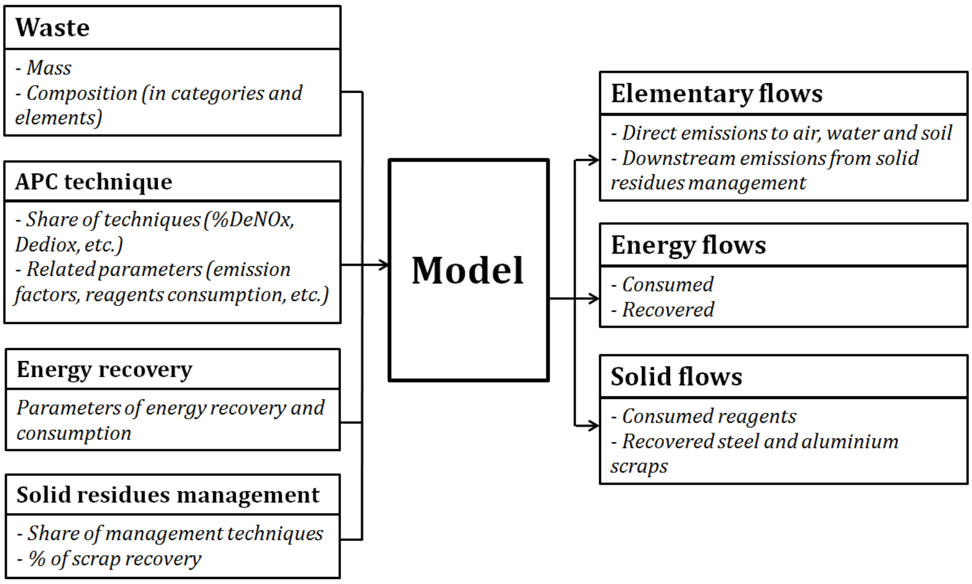

Figure 1. Scheme of the model implemented in WILCI. Main inputs (raw data) and outputs (elements of the resulting LCI)

Secondly, several worksheets are set for calculation purposes only. On the one hand, some of them are intended to hold data set as fixed (i.e. not user-modifiable) in the calculations: French waste composition by waste category, elemental composition of French waste categories, molar masses of elements and substances, coefficients of material use in incineration plants infrastructures, etc. On the other hand, two of these worksheets are intended to implement intermediate calculations for further use in the calculation of the resulting LCI: flue gas volume induced by MSW incineration and waste specific emissions.

Thirdly, the output inventory of elementary and economic flows calculated with respect to the user-defined functional unit is compiled in four distinct worksheets. In particular, one of these ("ResultingLCI_ForSimapro") reports the output LCI in a format adapted to its export to Simapro v8 for LCIA. This output LCI can also be exported, after some rearrangements, to other LCA softwares that contain the ecoinvent database (e.g. openLCA).

Table 1. Overview of worksheets in WILCI

Worksheet		**Description**
User-modifiable ?	**Name**	
YES	Waste Composition	Amount and composition, by waste category (functional unit)
	Emission Factor APC1	APC technology for dust and acid gases, and relative emission factors by technology
	Emission Factor APC2	APC technology for NOx and dioxins, and relative emission factors by technology
	Emission Factor APC3	Emission factors relative to CO and NMVOC, common to all APC technologies
	Reagents Consumption	Type and quantities of reagents consumed
	Energy	Parameters relative to energy consumption and production
	Bottom Ashes Management	Management of bottom ashes : proportion by management technique

	APC Residues Management	Management of APC residues : proportion by management technique
	Uncertainties	Calculation of uncertainty figures
NO (results)	ResultingLCI_ForSimapro	Resulting inventory, for export to the Simapro software
	Emissions_Waste	"Waste-specific" emissions
	Emissions_Technology	"Process-specific" air emissions and emissions relative to bottom ashes and APC residues management
	IntermediateExchanges	All other calculated intermediate exchanges
NO (for calculation purposes only)	Infrastructures	Coefficients of materials needed for building the incineration plant
	French Waste Composition	Average French MSW composition by waste category
	Waste Composition by Element	Composition in chemical elements, by waste category
	Transfer Coefficients	Transfer coefficients
	Molar Masses	Molar masses
	Vi_Calculation	Calculation of flue gas volume induced by the user-defined waste
	VM_Calculation	Calculation of flue gas volume induced by average French MSW
	Emissions_WasteSpecific	Step of calculation of “waste-specific” emissions, by use of transfer coefficients

3. USER-MODIFIABLE INPUT PARAMETERS

3.1 Functional unit: defining the waste under study

The functional unit is defined as the “thermal treatment of *x* tonnes of MSW”. The worksheet “Waste Composition” enables users to define both the value *x* (the amount of MSW that they consider to be incinerated) and the MSW composition, in terms of waste categories. As a default, French MSW composition is implemented: residual MSW (i.e. the share of MSW collected after source segregation and collection) stands for the main proportion of MSW incinerated (82%), while mixed non-hazardous waste from economic activities stand for 11% (ADEME, 2015). Both are mainly made of organic waste (39.6% in total wet waste), paper and cardboard (16.2%), textiles and sanitary textiles (12.9%) and plastics (11.7%; ADEME, 2010).

In total, 13 waste categories are distinguished in WILCI. Users may consider the French average MSW composition or rather set their own composition, either considering one unique waste category or a basket of waste categories. Considering each waste category, the relative elemental composition is set as fixed in a dedicated worksheet (“Waste composition by element”), considering average data for French MSW as the reference and distinguishing 35 chemical elements (ADEME, 2010).

3.2 APC techniques and process specific flows

3.2.1 APC techniques

The type of APC techniques considered to be implemented at the incineration plant can be specified by users respectively in worksheets “Emission Factors APC1” (dedicated to the abatement of dust and acid gases) and “Emission Factors APC2” (dedicated to the abatement of NOx and dioxins). Six APC techniques (respectively five) are distinguished considering the abatement of dust and acid gases (respectively considering the abatement of NOx and dioxins; Table 2). The average proportion of each APC technique in the French MSW incineration sector, considering data from 90 French incineration plants operated by SUEZ R&V France, TIRU and VEOLIA in the period 2012-2015, is set as a default in WILCI (representative of 73% of the total mass of MSW annually incinerated in France; Beylot et al., 2017). In particular, wet processes are the predominant acid gas treatment technique (39% of the total mass of MSW annually incinerated), while Selective Catalytic Reduction (SCR) stands for the predominant DeNOx technique. Users are given the possibility to change these default proportions, with a view to considering either a single APC technique or a specific basket of APC techniques in their LCA study.

Table 2. APC techniques distinguished in WILCI

Abatement of dust and acid gases	Abatement of NOx and dioxins
Bag filter + Dry processes	SCR (low temperature) with use of reagents for dioxins abatement
Electrofilter + Bag filter + Dry processes	SCR (high temperature) without use of reagents for dioxins abatement
Electrofilter + Wet processes with aqueous output	SCR (high temperature) with use of reagents for dioxins abatement
Electrofilter + Wet processes with dry output	SNCR with use of reagents for dioxins abatement
Bag filter + Semi-wet/semi-dry processes	Use of reagents for dioxins abatement (no DeNOX)
Other techniques	-

3.2.2 Process-specific emission factors

Air emission factors relative to NOx, NH_3 and dioxins (in g / tonne of waste) can be set by users as a function of NOx and dioxins abatement techniques. Similarly, users have the possibility to specify dust emission factors as a function of dust abatement techniques, and CO and NMVOC emission factors (independently of APC techniques). As a default, French average APC-specific emission factors are implemented in WILCI, considering data from 90 French incineration plants in the period 2012-2015 (Beylot et al., 2017).

3.2.3 Process-specific consumption of reagents

Users may either directly specify the masses of reagents consumed through the incineration process (by tonne of MSW incinerated), or instead use the WILCI calculator to estimate these quantities (as a function of APC techniques and waste composition defined by users in previous steps). Considering each APC technique, several reagents may be used. The relative proportions of reagents are set by default with respect to each APC technique, considering average data from 90 French incineration plants in the period 2012-2015 (Beylot et al., 2017). For example, regarding SNCR for DeNOx, as a default 64% of MSW incineration plants are considered to use urea (respectively 36% to use ammonia), based on mass-weighted average data for France. Masses of reagents consumed are then estimated considering both the stoechiometry of abatement reactions and “efficiency factors” set according to expert judgement (Beylot, 2017).

3.3 Energy

In worksheet "Energy", users can specify how much waste (in %) is treated in incineration plants with energy recovery as electricity, heat and Combined Heat and Power (CHP), and how much waste is incinerated without energy recovery. Default proportions relative to France are implemented in WILCI, considering average data from 90 French incineration plants in the period 2012-2015 (Beylot et al., 2017). In particular, 2/3 of MSW are incinerated in plants with CHP. In addition, considering each energy recovery technique, efficiencies in recovery for both delivery to the grid/network and use at the plant must be implemented as a percentage of the input waste Lower Heating Value (LHV). Again, average data for France are reported as default values, for modification by users if needed.

Moreover, users can specify the total electricity demand relative to MSW incineration (required for flue gas treatment, steam generator, etc.), and the potential additional energy consumption respectively for SCR implementation (natural gas) and bottom ash descrapping (electricity and diesel). Default coefficients of consumption are pre-implemented, respectively representative of the French MSW incineration sector (regarding total electricity demand for MSW incineration and natural gas for SCR; Beylot et al., 2017), and drawn from the literature (regarding bottom ash descrapping; Allegrini et al., 2015).

3.4 Solid residues management

Users can describe the main features of solid residues downstream treatment in worksheets "Bottom Ashes Management" and "APC Residues Management". The following input parameters can be entered: the proportions of steel and aluminium scraps recovered from bottom ashes (respectively 75 and 50% as a default for France; CEREMA, 2014); the proportions of descrapped bottom ashes respectively valorized in road construction and derived to landfills (respectively 81% and 19% as a default for France; CEREMA, 2014); the proportions of APC residues respectively landfilled and used as bakfills for old German salt mines (respectively 70% and 22% as a default for France, the remaining share being disposed of according to other techniques; AMORCE, 2012); and finally transport distances to disposal sites.

3.5 Uncertainty

In WILCI, uncertainty on the resulting LCI inputs and outputs is quantified considering a semi-quantitative approach (so-called "pedigree approach"), similarly to what is done in the ecoinvent LCI database. This approach consists in the combination of two types of uncertainties: i) the basic uncertainty represented by a probability density function (PDF) and that stands for the epistemic and systematic uncertainty and; ii) the additional uncertainty that qualifies the fact that the used datum does not represent the system under study. Additionnal uncertainty is coded through five characteristics: reliability, completeness, temporal correlation, geographical correlation and further technological correlation. For a detailed description of the pedigree approach, readers should refer to Weidema and Wesanes (1996) and Muller et al. (2016a).

In WILCI, a lognormal PDF is chosen to model uncertainty on LCI inputs and outputs (lognormal PDF is used as the default distribution in the ecoinvent database; see Frischknecht et al., 2005, and Muller et al., 2017). If available to the users, information on uncertainty can be implemented; if not, default basic uncertainty factors can instead be used. Furthermore, when the used datum does not represent the system under study, its quality can be coded so that default additional uncertainty factors are considered. Default basic and additional uncertainty factors used in WILCI are the ones developed by Muller et al. (2016b) as an update to the uncertainty factors used in the ecoinvent database.

4. MAIN CALCULATIONS

As usually considered in the LCA of MSW incineration, direct emissions from the incineration plant to the environment are calculated differentiating between so-called "waste-specific" and "process-specific" emissions (Riber et al., 2008; Astrup, 2015; Doka, 2013). Moreover, economic flows (reagents consumed and energy exchanged with the grid/network) are calculated to be further modelled by use of LCI databases. Finally, emissions from bottom ashes and APC residues management are calculated from solid residues mass and composition, by use of an additional external Excel-model.

4.1 Waste-specific emissions

Transfer coefficients enable to express the proportion of each input element that is transferred to the output compartments (gas, liquid, solid; Riber et al., 2008; Astrup, 2015; Doka, 2013). The mass of any element *k* transferred to the output compartment *j* is calculated according to:

Equation 1

$$\mathrm{Emission}\,(\mathrm{k},\mathrm{j}) = Mass_{Waste} \times \sum_{c=1}^{C_b}[Composition_{Waste}(c) \times Composition\,(c,k) \times TC_{Combustibles}(k,j)]$$

With:

Emission (k,j) the mass of element *k* transferred to compartment *j*;

$Mass_{waste}$ the mass of the input waste, considered to be incinerated;

$Composition_{Waste}\,(c)$ the composition of the input waste in combustible waste category *c*;

Composition (c,k) the composition of waste category *c* in element *k*;

$TC_{Combustibles}\,(k,j)$ the transfer coefficient of element *k* to compartment *j*, with respect to combustible waste fractions;

Cb the number of combustible waste categories (that is, "not inert").

In WILCI, transfer coefficients relative to wet processes are derived from Doka (2013) and set as fixed in worksheet "Transfer Coefficients". Regarding several chemical elements (S, Cl, F, Cd and Tl), Doka's transfer coefficients to air have been adapted to better represent the French MSW incineration sector, considering data of air emissions for 90 French incinerators in the period 2012-2015 (Beylot et al., 2017). Moreover, transfer coefficients relative to dry and semi-wet/semi-dry techniques have been approximated from Doka's transfer coefficients relative to wet processes, assuming that emissions to water (in wet processes) are instead transferred to solid residues (in dry and semi-wet/semi-dry processes). Similarly to the case of wet processes, regarding incinerators equipped with dry and semi-wet/semi-dry techniques, transfer coefficients to air have specifically been calculated relatively to S, Cl, F, Cd and Tl, considering data of air emissions for 90 French incinerators in the period 2012-2015 (Beylot et al., 2017). Finally, as a complement, transfer coefficients of Hg to air are set as a function of dioxins abatement technique (distinguishing with and without dioxins abatement), again considering data relative to the French MSW incineration sector.

4.2 Process-specific emissions

Air emissions of dioxins, particles, NMVOC, CO, and thermal NOx are determined both by operating conditions and waste composition (Astrup, 2015; Doka, 2013). These output flows have usually been called "process-specific" in the LCA of MSW incineration, and calculated considering that a given quantity of emissions is attributed to each kg of MSW incinerated, whatever the composition of the waste under study (Beylot et al., 2013).

In WILCI, the allocation approach developed by Doka (2013) is considered. That is, dioxins, particles, NMVOC and CO air emission factors are allocated to waste categories as a function of their induced flue gas volume relatively to average MSW, calculated in worksheet "Vi_Calculation". Moreover, thermal NOx caused by the incineration of a given waste fraction is assumed to be proportional to the input of combustion air required by the combustion of this specific waste fraction.

4.3 Link to standard LCI database for background processes

4.3.1 Background processes

The flows of reagents consumed, energy exchanged (respectively delivered to the grid/network and consumed), and scraps recovered for recycling are calculated as a function of MSW considered to be incinerated (the functional unit), and eventually reported in worksheet "IntermediateExchanges".

Quantities of materials required for the plant infrastructure and reagents consumed for APC are directly calculated from their dedicated user-modifiable worksheets (respectively "Reagents Consumption" and "Infrastructures"). In particular, coefficients of materials required for infrastructures, expressed in mass of materials / tonne of waste treated in worksheet "Infrastructures", are simply multiplied by the total user-defined mass of waste.

Similarly, energy production is calculated by multiplying the MSW LHV (in MJ) with user-defined efficiencies in recovery for both delivery to the grid/network and use at the plant (in %). Masses of aluminium and iron scraps recovered for recycling are calculated as a function of the content of bottom ashes in aluminium and steel, and further multiplied by recovery rates defined in worksheet "Bottom Ashes Management".

4.3.2 Emissions from solid residues management

Mass and composition of bottom ashes and APC residues are calculated as a function of the input waste composition in chemical elements and relative transfer coefficients (Equation 1). On the one hand, emissions from bottom ashes valorized in road construction are calculated considering emission factors from Allegrini et al. (2015), set as fixed as a proxy (in mg pollutant/kg bottom ash). On the other hand, regarding emissions from descrapped bottom ashes landfilling, WILCI users should additionally use the ecoinvent Excel "Calculation Tool for Municipal Solid Waste Incinerator MSWI" (Doka, 2002). WILCI provides the mass and composition of bottom ashes, in the form of a vector, for implementation in this ecoinvent Excel-tool.

Similarly, regarding APC residues derived to hazardous waste landfills, the output from WILCI is a vector describing the mass and composition of residues. Users must implement this vector in the ecoinvent Excel-tool (Doka, 2002) for the calculation of emissions from APC-residues landfilling.

5. RESULTING LCI

The inventory of inputs to and outputs from the system under study (the "thermal treatment of *x* tonnes of MSW") is on the one hand compiled in three worksheets ("Emissions_Waste", "Emissions_Technology" and "IntermediateExchanges"), in a disaggregated form that enables users to trace back which life cycle stage is responsible for the input and output flows. The first worksheet ("Emissions_Waste") reports waste-specific elementary flows from the incineration plant to the environment, calculated by use of transfer coefficients. The second worksheet ("Emissions_Technology") reports process-specific air emissions from the incineration plant to the environment (particles, CO, dioxins, etc.), together with emissions to water and soil from bottom ashes and APC residues downstream treatment (landfilling and valorization). Finally, the third worksheet ("IntermediateExchanges") reports intermediate exchange flows: use of materials for infrastructures and maintenance (steel, concrete, etc.), consumption of reagents, exchanges of energy, recovery of steel and aluminium scraps, transport of solid residues from the incineration plant to disposal, etc.

On the other hand, one single worksheet compiles the whole inventory of inputs and outputs in a format that can be exported to Simapro v8, for use in combination with ecoinvent v3 as a background database. The ecoinvent cut-off system model is considered in this worksheet: the inventory is allocated completely to the treatment of the waste, and therefore the burdens lay with the waste producer. Heat, electricity and materials co-produced through the incineration are considered to come burden-free. In case users want to model their inventory according to ecoinvent APOS (Allocation at the Point Of Substitution) and consequential modelling approaches, then they can use information on co-products (energy and material flows) that is contained in worksheet "IntermediateExchanges".

6. CONCLUSIONS

WILCI is an Excel-based tool dedicated to the LCA of MSW incineration in the French context. WILCI is filled with default data, primarily representative of the French MSW incineration sector, considering recent operational data at a large scale. In particular, data on APC technologies, emissions and energy, collected from 90 French incineration plants for the period 2012-2015, have been used for the definition of default data in WILCI. The calculation approach for the modelling of elementary and economic flows is primarily based on Doka (2013), whose work serves as a basis to the current ecoinvent LCIs of MSW incineration. In view of the similarities between French and other European MSW management systems, WILCI can be considered a robust tool to calculate the LCI of MSW incineration in the context of many European countries.

As an output, WILCI provides the LCI relative to the "thermal treatment of *x* tonnes of MSW" (as defined by the user). WILCI therefore needs to be combined with a LCA-software tool (e.g. Simapro v8), including standard LCI databases (e.g. ecoinvent v3), in order to derive environmental impact indicators.

WILCI is free of charge and can be obtained upon request to the developing team.

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