High temperature abatement of acid gases from waste incineration. Part II: Comparative life cycle assessment study

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1. Introduction

The performances of a new dolomitic sorbent, named Depurcal®MG, to be directly injected at high temperature in the combustion chamber of Waste-To-Energy (WTE) plants as an additional deacidification stage, were experimentally tested during full-scale commercial operation. Four plants located in Northern Italy were selected to this aim. They cover a wide range of treatment capacities, from 90,000 to 550,000 tonnes of waste per year. On average the treated waste consists of about 90% domestic waste, the rest being a variable mixture of other types of waste such as medical waste, commercial waste, automotive shredded residues, and sludge from wastewater treatment. The acid gases removal in the four WTE plants was previously based on sodium bicarbonate injection at low-temperature.

Results of the experimentations were promising, with an average removal efficiency of 23% for HCl, 71% for SO_2 and 63% for HF, and have been extensively described in Biganzoli et al. (2014). Furthermore, an average 30% saving of sodium bicarbonate injected in the flue gas treatment line was measured. In turn this has led to a different amount and partitioning of process residues, where the increase of fly ash removed in the first stage of dedusting (carried

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out by an electro-static precipitator) was compensated by a decrease of residual sodium salts collected in the second (based on a fabric filter, FF).

When making such modifications within industrial processes, that involve the use of different types of reactants, one has to make sure to avoid a burden shifting. An increase of the potential environmental impacts might in fact take place because of the different processes involved in the different life cycle stages. In this study a comparative Life Cycle Assessment (LCA) was thus performed between the traditional functioning of the plants, based on the sole sodium bicarbonate fed at low temperature, and the new one, where the dolomitic sorbent is injected at high temperature, and the sodium bicarbonate is still used, but at lower dosage. The production processes of both reactants were then considered and modelled, as well as the production of residues and their treatment and disposal.

LCA has been used extensively to evaluate the environmental performance of WTE technologies (among the others Boesch et al., 2014; Tonini et al., 2013; Rigamonti et al., 2012; Turconi et al., 2011; Morselli et al., 2008; Riber et al., 2008). Indeed, just a few LCA studies focus on flue gas cleaning processes in WTE plants. Damgaard et al. (2010) studied the historical development of air pollution control in waste incineration through LCA model-ling of eight different air pollution control technologies. In Scipioni et al. (2009), the LCA methodology was applied to an Ital-ian incineration line. Two different design alternatives were ana-lysed: an incineration system with dry flue gas cleaning and one with wet flue gas cleaning. Chevalier et al. (2003) compared two flue gas cleaning processes: a typical wet-type process (electro-static filter + scrubber) and the new transported droplets column process. Møller et al. (2011) investigated the selective non-catalytic reduction of nitrous oxides in a full-scale municipal solid waste incinerator.

In this LCA study, two scenarios of acid gases removal, i.e. the one based on sodium bicarbonate and the one based on the injection of Depurcal®MG at high temperature followed by sodium bicarbonate at low temperature have been compared. LCA in this case has been applied to primarily verify that the benefits associated with the use of the new dolomitic sorbent (i.e. the reduction in the use of sodium bicarbonate) do not hide drawbacks (e.g. associated with the production of the new sorbent). Moreover, the study aims to analyse the environmental consequences due to the change in the composition of the residues. Among the novelties of the study, primary data were collected on the two scenarios following an extensive experimentation carried out on full scale WTE plants (Biganzoli et al., 2014), as well as on the production of the dolomitic sorbent.

2. Materials and methods

2.1. Goal and scope definition

The two scenarios of acid gases removal, i.e. the one based on sodium bicarbonate ("Baseline Scenario"), and the one based on the injection of Depurcal®MG at high temperature, followed by sodium bicarbonate at low temperature ("+Depurcal Scenario"), have been compared by using the LCA methodology (ISO, 2006a,b). Indeed, the performance of the new dolomitic sorbent was found promising in terms of acid gases abatement efficiency and sodium bicarbonate saving (Biganzoli et al., 2014), but only an LCA study allows to evaluate whether a burden shifting is involved or not (e.g. due to the potential impacts associated with the production of the new sorbent).

The functional unit (FU) is one tonne of waste sent to incineration. For a consistent comparison, the raw gas concentration (i.e. the one prior to any abatement) of each acid gas is assumed equal in the two scenarios (i.e. 760.4 mg/m$_n^3$ for HCl, 35.1 mg/m$_n^3$ for SO_2 and 5.1 mg/m$_n^3$ for HF). The same applies to the concentra-tions at the stack (i.e. 2.5 mg/m$_n^3$ for HCl, 3.3 mg/m$_n^3$ for SO_2 and 0.01 mg/m$_n^3$ for HF), because they are kept constant by automatic plant operation management based on the Distributed Control Sys-tem (DCS). The latter is in fact regulated to continuously adjust the dosage of sodium bicarbonate in order to maintain a given set point concentration at the stack. In order to maintain the same effi-ciency in the abatement of the acid gases for the combustion of one tonne of waste, the two scenarios require a different amount of reactants, as explained in Biganzoli et al. (2014).

Being a strictly comparative LCA, the system boundaries include only the processes which differ between the two scenarios (Fig. 1), i.e. the production of the two reactants (including the raw materials extraction) and the treatment of the residues (fly ash and residual sodium salts). The additional CO_2 emission at the stack of the WTE plant due to the activation of the sodium bicarbonate was also included in the calculation. The difference in the electricity consumption of the feeding systems of the two reactants was instead not included in the analysis. According to the available data, this resulted negligible compared to the overall plant energy production.

Data used in the modelling of the foreground system are primary, derived from the experimental evaluations reported in Biganzoli et al. (2014) and from dolomitic sorbent production facility. For the modelling of the background processes (e.g. electricity production and transport) the datasets of ecoinvent (EI) database (Swiss Centre for Life Cycle Inventories, 2010) were used, as reported in detail in the "Inventory data" section. Capital goods are included in the analysis just for the background processes.

The study focuses on conditions and technologies applied in recent years: primary data refers in fact to the extensive experimentation carried out on full scale WTE plants in the years 2010–2012 described in Biganzoli et al. (2014) and to the production of the dolomitic sorbent as it happened in 2012. The geographical scope of the study (as defined in Astrup et al., 2014) is sub-plant, in particular the acid gas removal section.

Cases of multi-functionality were resolved by expanding the system boundaries to include avoided primary productions due to material and energy recovery from waste (Finnveden et al., 2009; EC JRC – IES, 2010). Details about the substituted products are given in the "Inventory data" section. Two sensitivity analyses were performed. The aim of the first one was to understand how the different management of the residues (i.e. fly ash and residual sodium salts treated separately or together) influences the results. A second sensitivity analysis investigated a possible further beneficial effect of the new dolomitic sorbent. As explained in Biganzoli et al. (2014), a better cleaning of the heat exchange surfaces inside the boiler was observed when using the new dolomitic sorbent, leading to a possible improvement of the electric energy production efficiency. Unfortunately it was hard to quantitatively measure such an effect, and only in one out of the four WTE plants it was possible to draft a preliminary estimate. Nevertheless, this aspect was considered of interest and so it was included in the second sensitivity analysis.

ReCiPe 2008 (Goedkoop et al., 2009) was selected as characterisation method for the evaluation of the potential environmental impacts associated with the two scenarios, together with the Cumulative Energy Demand – CED – (Hischier et al., 2010) to quantify the total energy consumption. ReCiPe has both midpoint (problem oriented) and endpoint (damage oriented) impact categories. For this study, we have chosen the impact categories (18) evaluated at the midpoint level. The time horizon of the LCA study is 100 years.

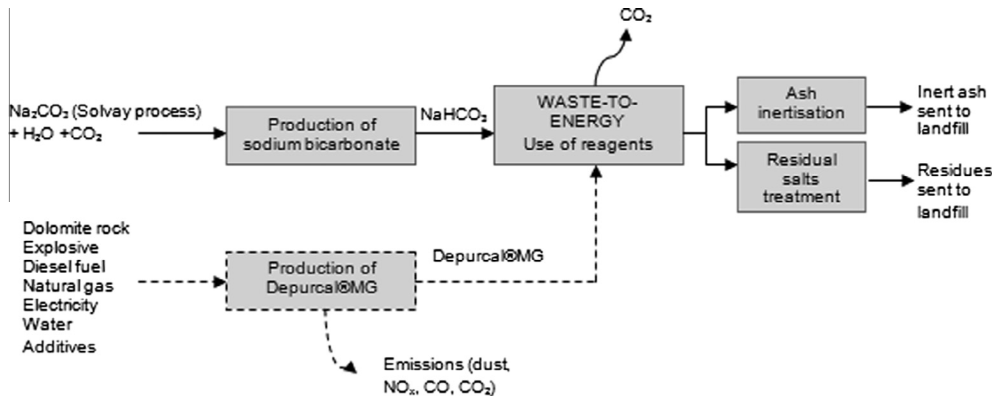

Fig. 1. Processes included within the LCA boundaries. *Note:* the production of Depurcal®MG is not included in the Baseline Scenario.

2.2. Inventory data

2.2.1. Production of the two reactants

The assumed feeding rates of sodium bicarbonate and Depurcal®MG were based on average results obtained in the four WTE plants (Como, Milano Silla 2, Valmadrera and Piacenza) (Table 1), which are:

- "Baseline Scenario": average feeding rate of 16.6 kg of sodium bicarbonate per FU.
- "+Depurcal Scenario": average feeding rate of 6.1 kg of Depurcal®MG per FU in the high temperature section, followed by 12.0 kg of sodium bicarbonate per FU at low temperature.

Data for the modelling of Depurcal®MG production were supplied directly by the producer. The production takes place in a plant located in the province of Cuneo (Italy). It includes four main steps:

1. Extraction of dolomite rock.
2. Pre-treatments (crushing, washing and screening);
3. Firing of the pre-treated dolomite rock to obtain dolomitic calcium oxide (i.e. calcination).
4. Selection and hydration of the dolomitic calcium oxide and subsequent milling and selective classification of the obtained hydroxide.

It has to be pointed out that other materials are produced in this facility, thus requiring an allocation of the inputs and outputs. In particular, while steps 1 and 2 are common to all typologies of materials produced at the plant, steps 3 and 4 are not. Inputs and outputs of steps 1 and 2 were therefore allocated based on the mass of dolomite rock sent to calcination and the mass of dolomite rock used directly for co-products.

Detailed inventory data are reported in Table 2. We specify that out of the total CO_2 emitted during calcination (step 3), 81% is due to decarbonation, while only 19% is due to the combustion of natural gas used to fuel the kiln.

For the modelling of sodium bicarbonate production, the approach suggested by Pacher et al. (2009) was adopted. It consists of two sequential production steps:

(1) Production of soda (Na_2CO_3) through the Solvay process.
(2) Reaction of soda with water and carbon dioxide to produce sodium bicarbonate with a high level of purity: $Na_2CO_3 + H_2O + CO_2 \rightarrow 2NaHCO_3$.

Step 1 was modelled by the EI dataset *Soda, powder, at plant/RER*. For step 2 the following inputs per one tonne of sodium bicarbonate were considered: 126 litres of water, 309 tonne of carbon dioxide and 336 MJ of electricity (Pacher et al., 2009).

The average distance between the production plant (located in the province of Livorno, Italy) and the four WTE plants was assumed equal to 330 km and the transport was modelled by using the EI dataset *Transport, lorry* > 16 t, *fleet average/RER*.

2.2.2. CO_2 emission due to the activation of sodium bicarbonate

CO_2 is produced during the activation of sodium bicarbonate when it is injected in the flue gas of the WTE plants, according to the following reaction:

$$2NaHCO_3 \rightarrow Na_2CO_3 + H_2O + CO_2$$

Stoichiometric calculation results in 262 g of CO_2 emitted per 1 kg of sodium bicarbonate, which were included in the analysis.

2.2.3. Treatment of the residues

Residual sodium salts, such as NaCl, NaF and Na_2SO_4, are produced in the reaction of sodium bicarbonate with acid gases. In

Table 1
Average feeding rate of sodium bicarbonate and Depurcal®MG and average production of fly ash and residual sodium salts in the four WTE plants for the two analysed scenarios (Biganzoli et al., 2014).

Scenario	Reactants feeding rate and residues production	Milano (Silla 2)	Valmadrera	Piacenza	Como
Baseline scenario	Sodium bicarbonate (average feeding rate: kg/t_{waste})	15.9	15.4	20.5	14.6
	Fly ash (average production: kg/t_{waste})	32	n.a.	n.a.	15
	Residual sodium salts (average production: kg/t_{waste})	17	n.a.	n.a.	11
+Depurcal scenario	Depurcal®MG (average feeding rate: kg/t_{waste})	4.0	8.5	4.5	7.5
	Sodium bicarbonate (average feeding rate: kg/t_{waste})	9.9	9.0	17.1	11.8
	Fly ash (average production: kg/t_{waste})	35	n.a.	n.a.	17.5
	Residual sodium salts (average production: kg/t_{waste})	14	n.a.	n.a.	8

n.a. Not available.

Table 2
Inventory data for the production of 1 tonne of Depurcal®MG (data referred to year 2012).

Input or output	Amount	Modelling in the software[a]
Step 1: extraction of dolomite rock		
Input of dolomite rock (t)	1.6	Substance: dolomite, in ground
Explosive consumption (kg)	0.07	EI dataset: blasting/RER
Diesel fuel consumption (hydraulic drilling machines, bulldozers, dumpers, excavators) (MJ)	16.9	EI dataset: diesel, burned in building machine/GLO
Step 2: pre-treatments of dolomite rock (crushing, washing and screening processes)		
Electricity consumption (kW h)	0.76	EI dataset: electricity, medium voltage, at grid/IT
Water consumption (replenish of washing-up water) (l)	63.5	EI dataset: water, unspecified natural origin, IT
Coagulant chemical (waste water treatment plant) (g)	5.9	EI dataset: aluminium sulphate, powder, at plant/RER
Flocculant chemical (waste water treatment plant) (g)	3.6	EI dataset: acrylonitrile from Sohio process, at plant/RER
Step 3: calcination of pre-treated dolomite rock to produce dolomitic calcium oxide		
Heat consumption in kiln (Mcal)	605	EI dataset: natural gas, high pressure, at consumer/IT
Electricity consumption in kiln (kW h)	23.7	EI dataset: electricity, medium voltage, at grid/IT
Particulates emission from kiln (kg)	0.010	Substance: particulates, <10 μm
NO_X emission from kiln (kg)	0.083	Substance: nitrogen oxides
CO emission from kiln (mg)	0.039	Substance: carbon monoxide
CO_2 emission from kiln (t)	0.750	Substance: carbon dioxide
Step 4: selection and hydration of the dolomitic calcium oxide and subsequent milling and selective classification of the obtained hydroxide		
Electricity consumption (kW h)	17.5	EI dataset: electricity, medium voltage, at grid/IT
Water consumption (used for hydration) (m^3)	0.370	EI dataset: water, unspecified natural origin, IT
Particulates emission (treatments + in silo storage) (g)	3.454	Substance: particulates, <10 μm
Transport of the final product to the WTE plant (t km)	260	EI dataset: Transport, lorry > 16 t, fleet average/RER

[a] EI = ecoinvent, RER = European context, IT = Italian context, GLO = Global context.

the presence of a double filtration system, that is, when the fly ash is preliminarily separated from the flue gas in an upstream filter, such salts are collected in a second filter. This means that the two streams can be delivered to different treatment or disposal processes. This is what happens in the WTE plants of Como and Milano (Silla 2), whereas the flue gas abatement line in Valmadrera is based on a single filtration. Indeed, the WTE plant of Piacenza has a double filtration system, but the output streams are mixed together and stored in the same silo prior to disposal.

Based on the data of Como and Milano Silla 2 WTE plants (Table 1), the following average amounts of residues were included in the analysis:

- "Baseline Scenario": 23.5 kg/FU of fly ash and 14.0 kg/FU of residual sodium salts.
- "+Depurcal Scenario": 26.3 kg/UF of fly ash and 11.0 kg/FU of residual sodium salts.

Fly ash undergoes an inertisation process, assumed to take place in the same site of the WTE plant. The inertisation of 1 kg of fly ash requires 0.225 l of water (modelled by EI dataset *Water*, *unspecified natural origin*, *IT*) and 0.07 kg of hydrated lime (modelled by EI dataset *Lime*, *hydrated*, *loose*, *at plant/CH*) (Rigamonti et al., 2012). After inertisation, the fly ash is sent to Germany for backfilling of mines. The average transport distance was assumed equal to 600 km and the transport was modelled by using the EI dataset *Transport*, *lorry* > 16 t, *fleet average/RER*. The backfilling was modelled with the EI dataset *Disposal*, *hazardous waste*, 0%*water*, *to underground deposit/DE*.

Residual sodium salts are sent for recovery to the Solval platform at Rosignano Marittimo in the province of Livorno. Here the NEUTREC® process allows for the production of a brine (to be reused by Solvay for sodium carbonate production) and of some hazardous solid residues that are landfilled. The average distance between the WTE plants and the Solval platform is the same as the one for sodium bicarbonate delivery (330 km) and the transport was modelled by the EI dataset *Transport*, *lorry* > 16 t, *fleet average/RER*. The treatment of 1 tonne of residual sodium salts allows the recovery of 743 kg of NaCl and it requires 30 kW h of electricity (Turconi et al., 2011). Recovered (i.e. avoided) NaCl was modelled by the EI dataset *Sodium chloride*, *powder*, *at plant/RER*. The residues of the treatment (i.e. 146 kg per tonne of residual sodium salts) are disposed in a landfill located at 300 km. The transport was modelled by EI dataset *Transport*, *lorry* 3.5–16 t, *fleet average/RER*, whereas the landfill disposal by a dataset derived from the EI one *Disposal*, *average incineration residue*, 0% *water*, *to residual material landfill/CH*.

A sensitivity analysis was performed to understand how a different management of the residues might influence the results, and in particular the focus was on the case where a single filtration is in place, not allowing for a separate treatment of the two residual streams. In such a situation the mixed stream cannot be treated in the Solval platform because of the high amount of fly ash, and so it is landfilled, after a simple inertisation process.

3. Results

3.1. Life cycle impact assessment results

Fig. 2 shows, for each impact category, the relative percent change between the two scenarios calculated as

$$\Delta(\%) = (\mathrm{Tot}_{i+\mathrm{Depurcal}} - \mathrm{Tot}_{i,\,\mathrm{baseline}})/\mathrm{Tot}_{i,\,\mathrm{baseline}} * 100$$

where Tot_i indicates the potential impact of category i in the Baseline Scenario ($\mathrm{Tot}_{i,\ \mathrm{baseline}}$) or in the +Depurcal Scenario ($\mathrm{Tot}_{i,\ +\mathrm{Depurcal}}$).

It is evident how some potential impacts increase and others decrease when using the dolomitic sorbent. Improvements are observed for Water depletion (−22.1%), Ecotoxicity (from −13.0% to −8.4% depending on the type of ecotoxicity), Terrestrial acidification (−10.0%), Human toxicity (−9.2%), Marine eutrophication (−7.7%), and Freshwater eutrophication (−7.6%). On the contrary, potential impacts increase for climate change (+16.4%), Ozone depletion (+16.2%), Mineral resource depletion (+10.4%), Natural land transformation (+9.6%), Agricultural land occupation (8.1%), Fossil depletion (+8.1%), and CED (+7.9%). We can assume that relative percent changes in the remaining impact categories are included within the uncertainty of the modelling, being lower than 5%. Climate change (Fig. 3) and Ozone depletion increase due to the relevant potential impacts associated with the Depurcal®MG production (22% and 16% on the total, respectively). The same applies to Fossil depletion and CED, where the contribution of the dolomitic sorbent production is about 10%. For Climate change,

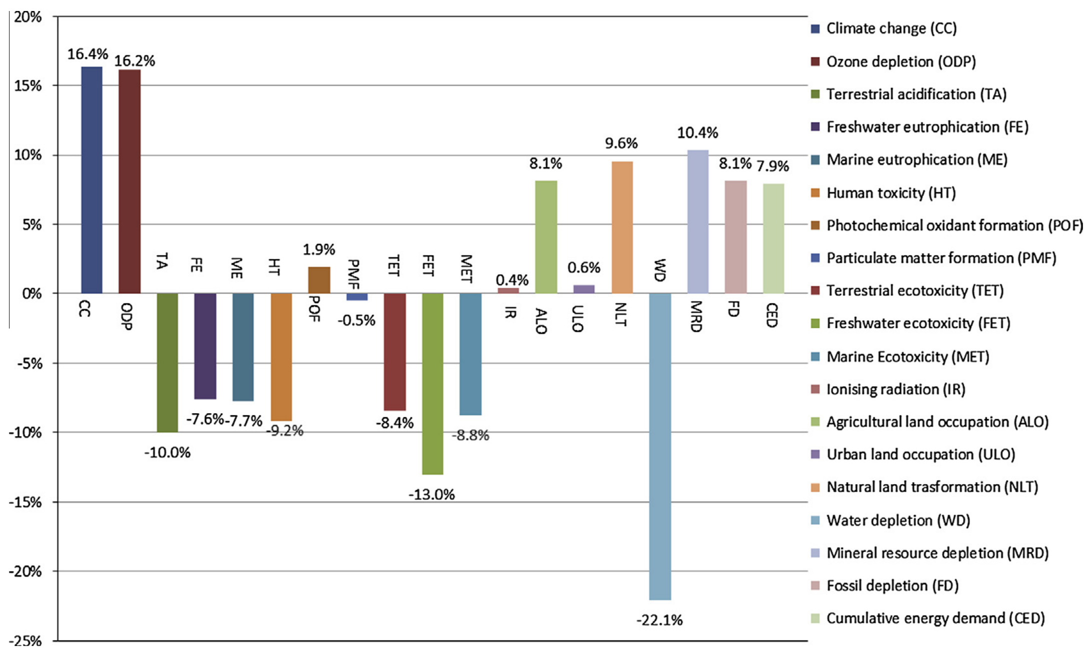

Fig. 2. Relative percent change between +Depurcal Scenario and Baseline Scenario (a positive value means that the impact of the +Depurcal Scenario is larger than that of the Baseline Scenario; vice versa for a negative value).

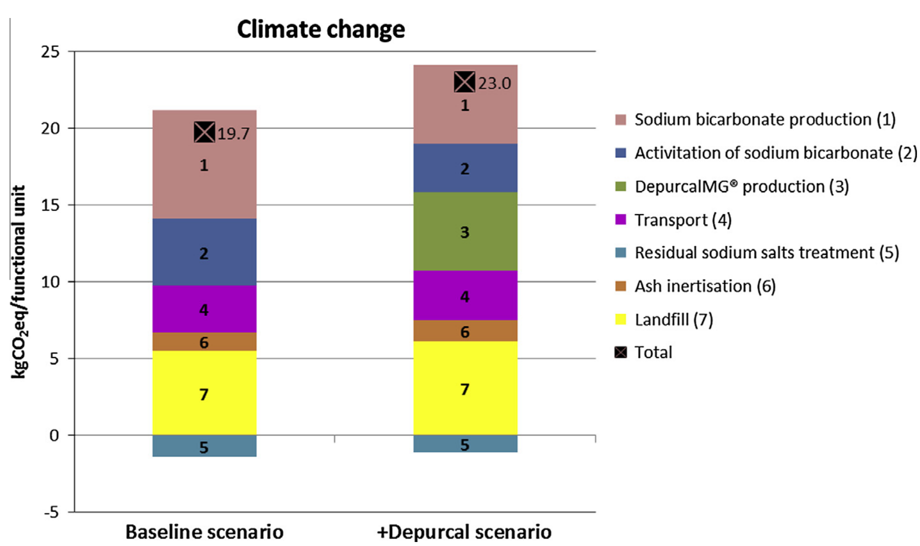

Fig. 3. Contribution analysis to the potential impact Climate change.

the contribution of the Depurcal®MG production is mainly (90%) due to the decarbonation of the dolomite, a process that occurs in the kiln releasing intrinsically a large amount of CO_2. As this process cannot be avoided, it is quite impossible to decrease the emission of CO_2. In the case of Ozone depletion, the main contribution (74%) to the potential impact associated with Depurcal®MG production is instead the natural gas used to fire the kiln.

However, the relative percent change should be read together with the difference expressed in absolute terms. Table 3 shows that for most of the potential impacts such differences are very modest. We can then conclude that the comparison between the two scenarios does not show systematic differences. This means that the benefits of the saving of sodium bicarbonate achieved in the +Depurcal scenario are compensated by the increase of the impacts for the management of the residues and for the production of the dolomitic sorbent.

3.2. Interpretation

A first sensitivity analysis was performed to understand how a different management of the residues may influence the results. A flue gas abatement line based on a single filtration layout, instead of the double filtration one, was considered in this analysis. The two new scenarios are named "Baseline FF" and "+Depurcal FF". The modelling of these two scenarios differs from that of Baseline and +Depurcal Scenarios only for the fact that residual sodium salts are no more sent to recovery. Instead, they are sent together with fly ash to inertisation and then to Germany for backfilling of mines. Results show that the absolute values of the potential impacts are still very similar for the two scenarios (Table 3). However, in this case, the +Depurcal FF Scenario allows for a reduction in most of the impact categories compared to the Baseline FF Scenario (Fig. 4). This reduction is more than 10% for 8 impact categories,

Table 3
Impacts (in absolute terms) associated with the analysed scenarios (expressed per functional unit).

Impact category (unit of measure)	Baseline Scenario	+Depurcal Scenario	Baseline FF Scenario	+Depurcal FF Scenario	+Depurcal + kW h Scenario
Climate change (kg_{CO2eq})	19.7	23.0	26.0	27.9	16.6
Ozone depletion ($kg_{CFC\text{-}11eq}$)	9.9E−07	1.2E−06	1.3E−06	1.4E−06	2.3E−07
Terrestrial acidification (kg_{SO2eq})	9.1E−02	8.2E−02	1.1E−01	1.0E−01	7.8E−02
Freshwater eutrophication (kg_{Peq})	6.9E−03	6.4E−03	8.7E−03	7.8E−03	6.4E−03
Marine eutrophication (kg_{Neq})	4.4E−03	4.1E−03	6.9E−03	6.0E−03	3.9E−03
Human toxicity ($kg_{1,4\text{-}DCBeq}$)	5.1	4.7	6.9	6.0	4.6
Photochemical oxidant formation (kg_{NMVOC})	7.5E−02	7.6E−02	9.8E−02	9.5E−02	6.9E−02
Particulate matter formation (kg_{PM10eq})	4.1E−02	4.1E−02	5.7E−02	5.3E−02	3.9E−02
Terrestrial ecotoxicity ($kg_{1,4\text{-}DCBeq}$)	2.2E−03	2.0E−03	2.2E−03	2.0E−03	1.9E−03
Freshwater ecotoxicity ($kg_{1,4\text{-}DCBeq}$)	1.9E−01	1.7E−01	1.8E−01	1.5E−01	1.7E−01
Marine ecotoxicity ($kg_{1,4\text{-}DCBeq}$)	1.4E−01	1.3E−01	1.6E−01	1.4E−01	1.3E−01
Ionising radiation (kg_{U235eq})	1.1E + 00	1.1E + 00	2.4E + 00	2.1E + 00	1.1E + 00
Agricultural land occupation (m^2 a)	3.8	4.1	6.0	5.8	4.1
Urban land occupation (m^2 a)	1.6E−01	1.6E−01	2.3E−01	2.2E−01	1.6E−01
Natural land transformation (m^2)	2.7E−03	3.0E−03	3.9E−03	3.9E−03	1.5E−03
Water depletion (m^3)	3.8E−01	3.0E−01	4.7E−01	3.7E−01	2.5E−01
Mineral resource depletion (kg_{Feeq})	4.2	4.6	7.2	7.0	4.6
Fossil depletion (kg_{oileq})	4.5	4.9	6.3	6.3	2.5
CED (MJ)	232	250	338	334	139

between 5% and 10% for 3 impact categories and less than 5% for 6 impact categories. On the contrary, the +Depurcal FF Scenario implies an increase in Climate change and Ozone depletion of about 7%.

Comparing the +Depurcal Scenario with the +Depurcal FF Scenario and the Baseline Scenario with the Baseline FF Scenario, we can notice that the scenarios with the double filtration have lower potential impacts than the scenarios with the single filtration (Table 3). This means that the recovery of the residual sodium salts allows for a reduction in all the potential impacts.

A second sensitivity analysis was carried out to take into account the possible improvements of the energy performances of the WTE plants when the dolomitic sorbent is used. As explained in Biganzoli et al. (2014), a better cleaning of the heat exchange surfaces inside the boiler was observed when using the dolomitic sorbent. In the Piacenza plant an increased electric energy production of 15 kW h per tonne of incinerated waste was observed, which was the value included in the sensitivity analysis.

By adopting a consequential approach in the LCA and considering the Italian context (Rigamonti et al., 2013), the avoided electricity was modelled as produced in a combined cycle plant fed with natural gas (EI dataset: *Natural gas, at combined cycle plant, best technology/RER*). The new scenario is called "+Depurcal + kW h".

The absolute values for this new scenario are reported in Table 3. One can observe that most of the potential impacts are lower than those of the +Depurcal Scenario. Significant reductions are observed for Ozone depletion (−80%), Fossil depletion (−49%), Natural land transformation (−48%), CED (−44%), Climate change (−28%), and Water depletion (−17%).

Moreover, Fig. 5 shows that in the comparison with the Baseline Scenario, there is also a reduction in most of the potential impacts (17 out of 19), including the Climate change. Significant reductions are observed for Ozone depletion (−76%), Fossil depletion (−45%), Natural land transformation (−43%), CED (−40%), Water depletion (−35%), and Climate change (−16%).

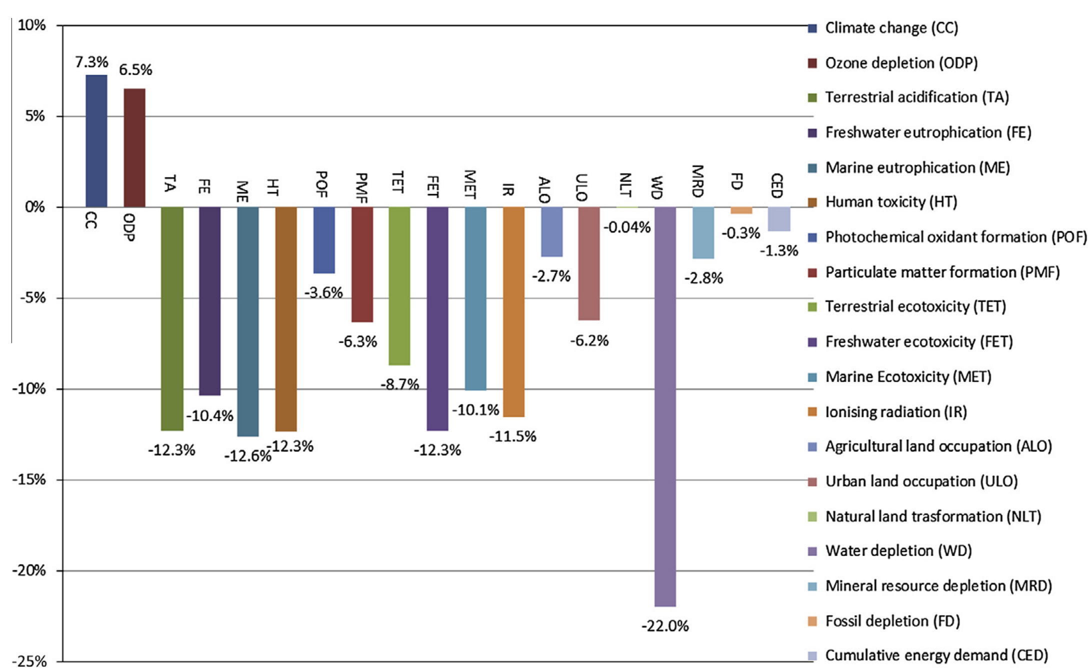

Fig. 4. Relative percent change between +Depurcal FF Scenario and Baseline FF Scenario (a positive value means that the impact of the +Depurcal FF Scenario is larger than that of the Baseline FF Scenario; vice versa for a negative value).

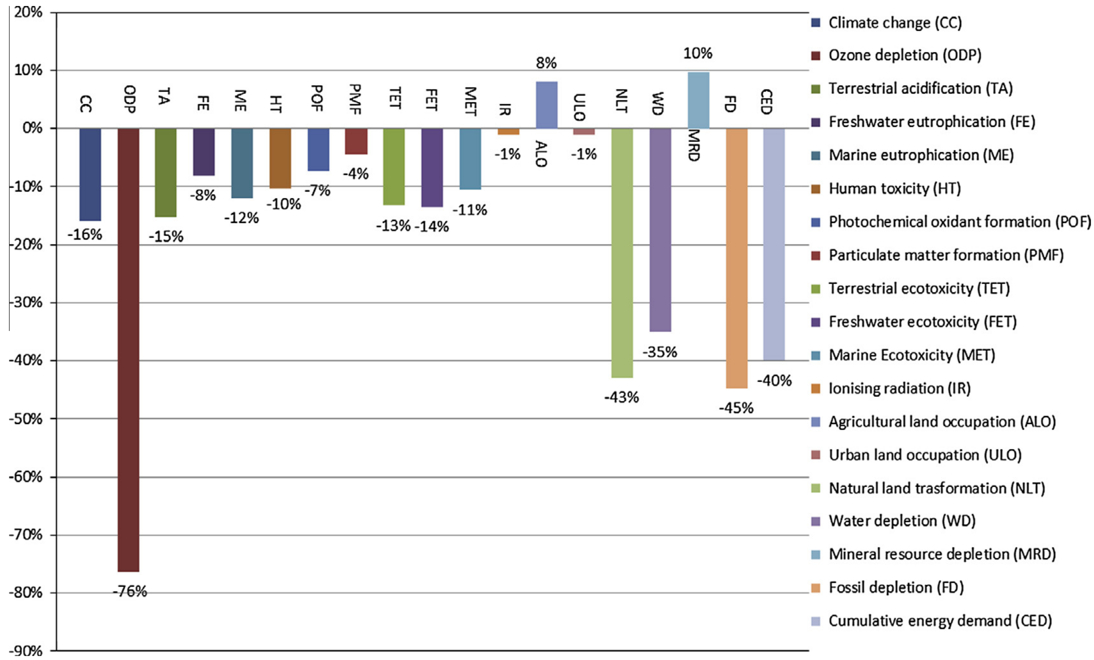

Fig. 5. Relative percent change between +Depurcal + kW h Scenario and Baseline Scenario (a positive value means that the impact of the +Depurcal + kW h Scenario is larger than that of the Baseline Scenario; vice versa for a negative value).

We can conclude that the potential increase of the specific electric energy production leads to improvements of the system environmental performance.

4. Conclusions

The performances of a new dolomitic sorbent, named Depurcal®MG, to be directly injected at high temperature in the combustion chamber of WTE plants as a pre-cleaning stage, were experimentally tested during full-scale commercial operation. Results of the experimentations have been described in Biganzoli et al. (2014). In this paper, the two scenarios of acid gases removal, i.e. the baseline based on sodium bicarbonate, and the new one, based on the injection of Depurcal®MG at high temperature, followed by sodium bicarbonate at low temperature, were compared by using the LCA methodology.

The results of the LCA show that the potential impacts of the +Depurcal Scenario are not considerably different from those of the Baseline Scenario. These differences are for 8 impact categories in favour of the +Depurcal Scenario, and for 7 impact categories in favour of the Baseline Scenario. This means that the benefits associated with the sodium bicarbonate saving achieved in the +Depurcal scenario are compensated by the increase of the impacts associated with the residues management and by the impacts associated with the production of the new dolomitic sorbent.

The recovery of the residual sodium salts allows an improvement in the performance of the system. In fact, under the assumption that such salts are instead inertised and disposed, the potential impacts will increase. This means that when the flue gas treatment line is based on a single filtration, the use of the dolomitic sorbent will result in the best performances in all the impact categories, except for climate change and ozone depletion.

If the use of the Depurcal®MG allows for an increase in the specific energy production, as it was observed in one of the WTE plants, then 17 impact categories out of 19, including the Climate change, are reduced in the comparison with the traditional operation. In any case, further experimental tests should be performed to investigate in depth the correlation between the use of the new dolomitic sorbent and the better cleaning of the heat exchange surfaces inside the boiler, which in turn gives a possible improvement of the electricity production efficiency.

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References

Astrup, T.F., Tonini, D., Turconi, R., Boldrin, A., 2014. Life cycle assessment of thermal Waste-to-Energy technologies: review and recommendations. Waste Manage. http://dx.doi.org/10.1016/j.wasman.2014.06.011.

Biganzoli, L., Racanella, G., Rigamonti, L., Marras, R., Grosso, M., 2014. High temperature abatement of acid gases from waste incineration. Part I: Experimental tests in full scale plants. Waste Manage. http://dx.doi.org/10.1016/j.wasman.2014.10.019.

Boesch, M.E., Vadenbo, C., Saner, D., Huter, C., Hellweg, S., 2014. An LCA model for waste incineration enhanced with new technologies for metal recovery and application to the case of Switzerland. Waste Manage. 34, 378–389. Chevalier, J., Rousseaux, P., Benoit, V., Benadda, B., 2003. Environmental assessment of flue gas cleaning processes of municipal solid waste incinerators by means of the life cycle assessment approach. Chem. Eng. Sci. 58, 2053–2064.

Damgaard, A., Riber, C., Fruergaard, T., Hulgaard, T., Christensen, T.H., 2010. Life-cycle-assessment of the historical development of air pollution control and energy recovery in waste incineration. Waste Manage. 30, 1244–1250.

European Commission (EC) Joint Research Center (JRC) – Institute for Environment and Sustainability (IES), 2010. ILCD Handbook: General Guide for Life Cycle Assessment and Detailed Guidance, <http://lct.jrc.ec.europa.eu/assessment/publication> (accessed 15.03.12).

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manage. 91 (1), 1–21.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., Van Zelm, R., 2009. ReCiPe 2008: A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level, first ed. (version 1.08), Report I: Characterisation. <http://www.lcia-recipe.net>.

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T., 2010. Implementation of Life Cycle Impact Assessment Methods, Data v2.2, Ecoinvent Report N. 3. <http://www.ecoinvent.ch>.

ISO (International Organization for Standardization), 2006a. ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework.

ISO (International Organization for Standardization), 2006b. ISO 14044: Environmental Management – Life Cycle Assessment – Requirements and Guidelines.
Møller, J., Munk, B., Crillesen, K., Christensen, T.H., 2011. Life cycle assessment of selective non-catalytic reduction (SNCR) of nitrous oxides in a full-scale municipal solid waste incinerator. Waste Manage. 31, 1184–1193.
Morselli, L., De Robertis, C., Luzi, J., Passarini, F., Vassura, I., 2008. Environmental impacts of waste incineration in a regional system (Emilia Romagna, Italy) evaluated from a life cycle perspective. J. Hazard. Mater. 159, 505–511.
Pacher, C., Mocker, M., Weber-Blaschke, G., Quicker, P., Faulstich, M., 2009. Vergleichende ökologische Betrachtung verschiedener Einsatzstoffe bei Trockensorptionsverfahren zur Rauchgasreinigung. (Comparative ecological examination of different types of feedstock in dry sorbent injection processes for flue gas treatment). Final Report for the Federation of German Lime Industry. Technische Universität München-ATZ Entwicklungszentrum (in German).
Riber, C., Bhander, G.S., Christensen, T.H., 2008. Environmental assessment of waste incineration in a life-cycle-perspective (EASEWASTE). Waste Manage. Res. 26, 96–103.
Rigamonti, L., Grosso, M., Biganzoli, L., 2012. Environmental assessment of refuse-derived fuel Co-combustion in a coal-fired power plant. J. Ind. Ecol. 16 (5), 748–760.
Rigamonti, L., Falbo, A., Grosso, M., 2013. Improving integrated waste management at the regional level: the case of Lombardia. Waste Manage. Res. 31 (9), 946–953.
Scipioni, A., Mazzi, A., Niero, M., Boatto, T., 2009. LCA to choose among alternative design solutions: the case study of a new Italian incineration line. Waste Manage. 29, 2462–2474.
Swiss Centre for Life Cycle Inventories, 2010. The Life Cycle Inventory Data. Version 2.2
Tonini, D., Martinez-Sanchez, V., Astrup, T.F., 2013. Material resources, energy, and nutrient recovery from waste: are waste refineries the solution for the future? Environ. Sci. Technol. 47, 8962–8969.
Turconi, R., Butera, S., Boldrin, A., Grosso, M., Rigamonti, L., Astrup, T., 2011. Life cycle assessment of waste incineration in Denmark and Italy using two LCA models. Waste Manage. Res. 29, 78–90.