Reuse of process water in a waste-to-energy plant: An Italian case of study

Davide Gardoni, Arianna Catenacci, Manuela Antonelli *

Politecnico di Milano, DICA – Environmental Section, Piazza Leonardo da Vinci, 32, 20133 Milano, Italy

Received 26 January 2015
Accepted 4 May 2015
Available online 28 May 2015

A B S T R A C T

The minimisation of water consumption in waste-to-energy (WtE) plants is an outstanding issue, especially in those regions where water supply is critical and withdrawals come from municipal waterworks. Among the various possible solutions, the most general, simple and effective one is the reuse of process water. This paper discusses the effectiveness of two different reuse options in an Italian WtE plant, starting from the analytical characterisation and the flow-rate measurement of fresh water and process water flows derived from each utility internal to the WtE plant (e.g. cooling, bottom ash quenching, flue gas wet scrubbing). This census allowed identifying the possible direct connections that optimise the reuse scheme, avoiding additional water treatments. The effluent of the physical–chemical wastewater treatment plant (WWTP), located in the WtE plant, was considered not adequate to be directly reused because of the possible deposition of mineral salts and clogging potential associated to residual suspended solids. Nevertheless, to obtain high reduction in water consumption, reverse osmosis should be installed to remove non-metallic ions (Cl^-, SO_4^{2-}) and residual organic and inorganic pollutants. Two efficient solutions were identified. The first, a simple reuse scheme based on a cascade configuration, allowed 45% reduction in water consumption (from 1.81 to 0.99 $m^3\ t_{MSW}^{-1}$, MSW: Municipal Solid Waste) without specific water treatments. The second solution, a cascade configuration with a recycle based on a reverse osmosis process, allowed 74% reduction in water consumption (from 1.81 to 0.46 $m^3\ t_{MSW}^{-1}$). The results of the present work show that it is possible to reduce the water consumption, and in turn the wastewater production, reducing at the same time the operating cost of the WtE plant.

1. Introduction

Waste incineration implies high water intakes mainly for cooling, bottom ash quenching and flue gas wet scrubbing, usually supplied by municipal waterworks. Concerning the Italian context, common specific consumptions for waste-to-energy (WtE) plants are within 0.30 and 0.50 $m^3\ t_{MSW}^{-1}$ (Municipal Solid Waste) when water is not used for flue gas wet scrubbing, otherwise higher values, ranging from 1.80 to 2.00 $m^3\ t_{MSW}^{-1}$ are possible (Morselli et al., 2007; Scipioni et al., 2009). Water shortage problems are becoming more widespread and thus the reduction of water request in WtE plants is an outstanding issue (Ma et al., 2014). In fact, in several Directives (e.g. 75/442/EEC, 2004/35/EC, and 2008/98/EC), European Union established a responsibility common framework preventing damage to water resource, among the other environmental compartments, when dealing with waste policies (Cucchiella et al., 2014), and this can include the preservation of water bodies from the unnecessary exploitation. The topic of a coherent and responsible use of the water resource was also remarked in the recent ISO Standard 14046:2014 (Environmental management – Water footprint – Principles, requirements and guidelines).

In literature there is a lack of publications regarding this specific topic, as more urgent problems such as emission of atmospheric pollutants, global warming, acidification and eutrophication of water bodies, and public acceptance, are discussed (e.g. Cleary, 2009; Belboom et al., 2013; Passarini et al., 2014). As a consequence, water consumption extent is considered as one of the least important criteria if compared to the other potential impacts in the ecological footprint definition of WtE plants, especially where the water resource is easily available. The relevance of water consumption, in fact, depends on the specific conditions of the site location, as reported by Herva and Roca (2013) who underline how the environmental impact gains in significance in case of water scarcity. It should be also mentioned that there is a multiplicity of contaminants, released in wastewater flows by flue gas and bottom ash, displaying a relevant toxic action towards aquatic ecosystem and

* Corresponding author. Tel.: +39 02 2399 6407.
E-mail address: manuela.antonelli@polimi.it (M. Antonelli).

human health, such as heavy metals or some non-metallic ions (Cardoso et al., 2008; Sekito et al., 2015), which can impair the water resource for potable use; again, this negative impact gains in significance in case of water scarcity. In conclusion, available data are scarce and disaggregated; however, in those regions where water supply is critical and withdrawals come from munic-ipal waterworks, this aspect should be considered carefully.

Three different options to minimise water consumption in a WtE plant are identifiable, and they can be used one at the time or by defining an integrated approach in order to optimise the processes (e.g. Mohsen, 2004; Oliveira-Esquerre, 2011; Klemeš, 2012; McLarty et al., 2012):

- replacing wet technologies with dry technologies;
- finding alternative water sources such as surface runoff, rain water, surface water;
- replacing fresh water, especially if it is potable water, with reclaimed process water.

The first option allows a relevant water saving (up to 60–90%, considering the implicit low water consumption of dry technologies, as suggested by Deuster et al., 1994), but contextually it needs a significant and expensive upgrade of the technological structures of the WtE plant. It is clear that this approach is preferable during the design or the renovation of the plant, but it is not sustainable for an already operating plant. The use of alternative water sources is an attractive solution for its simplicity but it is strictly related to the local availability, that limits the interest in this option only to regions where fresh water is easily available. Actually, it does not represent an effective saving option, as it changes the supplying source, but it does not change the overall water request. Moreover, it does not decrease the production of wastewater that represents a relevant fraction of the water management costs. The third option, the reuse of reclaimed process water, can be effective and quite inexpensive, since it does not require any rele-vant modification in the WtE plant existing structures, and allows a real water saving since both the water consumption and discharge are reduced. Nevertheless, reuse is limited by legal constraints (emission limits) and technical constraints (compatibility of water quality with processes, meaning cooling, bottom ash quenching, flue gas wet scrubbing), which may require additional and complex treatments. These issues can be faced through methodologies aimed at assessing the sustainability of the above mentioned options, for water consumption reduction, in their complexity (e.g. economic/environmental models, life cycle assessment, eco-logical footprint, multi-criteria analysis). However, considering that the reuse of reclaimed process water has an impact mainly on water consumption and only secondarily on the incineration process, valuable results can be obtained with a simpler approach based on mass balances.

This work reports on a case of study for the reuse of the process water of a WtE plant sited in northern Italy in order to reduce fresh water consumption, with no modification of the plant layout. Preliminarily to mass balances, physical–chemical characterisation and flow rate measurement of fresh water and process water flows, derived from each utility internal to the WtE plant (e.g. cooling, bottom ash quenching, flue gas wet scrubbing), have been performed. Then, the potential direct recycle of the various process water flows has been considered, focusing on the possibility to simplify the layout and consequently the operation without intermediate specific water treatments. This reuse scheme implies the change from a 'single passage' to a 'cascade' configuration for water usage, but some constraints must be taken into account: when the water request is reduced, the concentration of pollutants in the final discharge increases, since their production depends mainly on the characteristics of MSW incinerated.

It should be stressed that the purpose of the paper is to discuss a topic that is not adequately described in the literature, even if water-use-related topics are becoming more and more important considering the challenges posed by climate changes. The paper shows that a reduction of the consumption of fresh water and of the related production of wastewater is possible without any structural modification of the WtE plant and, at the same time, evaluates the economic feasibility of the reuse approaches.

2. Materials and methods

2.1. WtE plant and water usage cycle description

The waste-to-energy plant studied burns approximately 280 t/d of MSW, into two parallel lines treating 43% (Line 1) and 57% (Line 2) of the incoming MSW. Each line consists of: moving grate furnace, combustion chamber recovering heat for the production of energy, and flue gas cleaning system. This includes: NO_x removal by catalytic reduction with ammonia, acid gas absorption by lime (alkaline cleaning), organic and inorganic micropollutants adsorption on granular activated carbon (GAC), particulate collection on baghouse filters and final acid gas cleaning by water (Line 1) and water and sodium carbonate (Line 2). The water used for the cooling of furnaces and hoppers is not recovered: it flows into pipes and is kept separated from MSW, ashes and flue gases; therefore no contamination occurs. Low-pressure jets of water coming out of quenching nozzles are used to cool the bottom ashes. Heat of combustion chambers is recovered for the production of steam for electricity generation: high purity water for the steam turbine is produced using ion exchangers.

The main utilities in the WtE plant, supplied by a municipal waterworks, have been identified based on the type of process and the related potential contamination of process water, in terms of both type of pollutants and their concentration.

As for sanitary facilities, wastewater can be directly discharged in the sewerage system, contrarily to the other flows that need further treatment in the WWTP (WasteWater Treatment Plant) located inside the WtE plant.

Some other water usages are present in the WtE plant, related to fire prevention system, garden irrigation, parking lot and vehicles washing, etc.

The WWTP removes heavy metals and suspended solids by a coagulation–sedimentation process. The WWTP, that is oversized from two to three times with respect to the influent flow rate, consists of two in-series reaction tanks (16 m^3 and 12 m^3), where $FeCl_3$, an anionic polyelectrolyte and a complexing agent are dosed, a settler (180 m^3, diameter: 10 m) and a final reaction tank for pH adjustment.

2.2. Process water characterisation

A quantitative characterisation of the process water coming from the various utilities internal to the WtE plant has been performed, measuring flow rates daily for 9 months using mechanical flow meters, except for the vapour and steam loss flows, which were estimated by mass balances with a residual error less than 5%.

A chemical and physical characterisation of the main process water flows was performed: at least 3 instant samples per day were collected for each monitored flow to take into account the variability related to the incinerated MSW characteristics. The monitoring campaign lasted about 30 days, with sampling collection about once a week. Measurements on the WWTP final effluent were carried out for 12 months, according to the enforced regulation.

The following parameters were measured for each sample: aluminium, chloride, chromium (total), copper, lead, mercury, nickel, sulfate, and zinc by Hach-Lange spectrophotometric kits; temperature, pH, alkalinity, hardness, conductivity, suspended solids according to Standard Methods (APHA et al., 2012).

2.3. Methodological approach

To develop effective water reuse schemes, in addition to a comprehensive review of the water-consuming processes, the following steps have been carried out.

- A quantitative and qualitative characterisation of fresh water and process water flows.
- The legal constraints have been assessed: the concentration of pollutants in the WWTP final effluent increases when overall WtE water request is reduced due to the related reduction of the flow rate discharged into the sewerage. As a consequence, it is necessary to quantify the specific production of pollutants for each identified internal utility of the WtE plant, and to define the lowest flow rate, i.e. the minimum admissible flow rate, that guarantees the respect of legal limits for the discharge of wastewater into the sewerage. The attention should be mainly focused on ions such as chloride and sulfate that cannot be removed with conventional technologies, while many heavy metals can be eliminated by well-known coagulation–precipita tion processes (Metcalf and Eddy, 2003; Kurniawan et al., 2006; Fu and Wang, 2011). To support this assumption, a verification of the WWTP functionality in the new conditions is also needed. In Italy, the limit for the discharge into the sewerage is 1200 mg L^{-1} for chloride and 1000 mg L^{-1} for sulfate. The min-imum admissible flow rate (Q_{min}) can be calculated as:

$$Q_{min} = F_{max}/C_{lim} \quad (1)$$

where F_{max} is the maximum daily amount of chloride or sulfate discharged [kg d^{-1}] and C_{lim} is the discharge concentration limit [kg m^{-3}] for the specific pollutant.

- The technical constraints have to be defined, since the quality of the reclaimed process water flows (flow rate, temperature and concentrations of pollutants, such as suspended solids and metals) has to be compatible with their destination.

Analysing each utility of the WtE plant, considering both their characteristics and legal and technical constraints, it is possible to identify the potential connections in order to build a water-usage-cascade configuration: this means that the flows of process water can be rearranged to obtain an efficient configuration which reduces the fresh water demand. It has to be noted that cascade configuration does not affect WtE plant operation, nor the specific water consumption of the single utility, but only the overall water consumption. If the cascade-configuration recovery efficiency is not satisfactory, a water recycle circuit can be designed: in this configuration the final effluent of the WWTP is reclaimed and recycled, but this implies the need for a high-efficiency purification treatment, typically a reverse osmosis process, mainly to remove salts responsible of scaling phenomena.

3. Results and discussion

3.1. Characteristics of process water

The main internal utilities identified in the WtE plant based on water usage are showed in Fig. 1, where average flow rates are reported too, concerning periods when both incineration units were on. The utility in Fig. 1 named "Other utilities" refers to minor flow rates, as described above, whose role is negligible from the point of view of both incineration process and water usage. The vapour and steam losses are mainly due to the flue gas cleaning system (80%), and secondarily to the bottom ash quenching (20%). The specific water consumption of the WtE plant is 1.81 m^3 per ton of MSW, which is comparable with literature data.

Starting from the water usages reported in Fig. 1, it was possible to aggregate the process water flows into two main groups considering the main pollution issues. In fact, contamination of the various flows depends on the process in which water is involved:

- contaminated flows, characterised by significant concentrations of heavy metals, coming from bottom ash quenching and flue gas cleaning (water and alkaline wet scrubbing) utilities;
- uncontaminated flows, which are not contacted with pollution sources and therefore not contaminated by heavy metals. They come from cooling, boiler and boiler water production (namely the ion exchange brine) utilities.

The flows coming from "Other utilities" and "Sanitary facilities" have been neglected in this assessment, considering: the low flow rates (about 8% of the overall water request), the discontinuity in their use, the difficulty of a representative collection due to their dispersion over the WtE plant area, the presence of organic pollutants in the sanitary effluents that would require specific treatments.

The measured concentrations of pollutants in contaminated flows are reported in Table 1. The high variability observed (standard deviations are in general high, for some parameters more than the 50% of the mean value; e.g. aluminium, lead, chromium, and zinc in bottom ash quenching wastewater) is due to the fact that the characteristics of process water depend on the characteristics of the MSW incinerated, which can change over a long period (Hjelmar, 1996; Jung et al., 2004). A similar behaviour was observed and reported in other WtE plants (Feng et al., 2007).

Uncontaminated flows (pH = 8.1 ± 0.4, conductivity: 225 ± 15 $\mu S\ cm^{-1}$, alkalinity: 85 ± 5 $mgCaCO_3\ L^{-1}$, hardness: 100 ± 10 $mgCaCO_3\ L^{-1}$, pollutants: below detection limits) have the same quality of fresh water, except for the temperature that is higher (40 °C for cooling water and 60–70 °C for boiler water, compared to 15 °C of fresh water).

The WWTP final effluent displayed concentrations under the legal limits for the discharge into sewerage (see Table 1) even for those inorganic ions that cannot be removed by conventional treatments, namely chloride (317 ± 116 mg L^{-1}, maximum value: 449 mg L^{-1}) and sulfate (269 ± 30 mg L^{-1}, maximum value: 306 mg L^{-1}).

3.2. Legal and technical constraints

Legal constraints are related to the efficiency of the WWTP. Water reuse implies a reduction of the total influent flow rate to the WWTP and, as a consequence, of the wastewater discharged. An increase of the concentration of pollutants that cannot be removed by the WWTP (i.e. chloride and sulfate) is therefore impli-cit in the final effluent, while the concentration of the other pollu-tants should be evaluated as a function of the specific characteristics of the treatment plant. Chloride and sulfate ions showed high concentration values especially in process water derived from bottom ash quenching and flue gas cleaning system, as reported in Table 1. Considering the highest measured concen-tration of chloride and sulfate, it was possible to calculate F_{max} and Q_{min} related to both anions. Assuming the most restrictive con-dition, Q_{min} resulted in 165 $m^3\ d^{-1}$; as a safety factor, a minimum

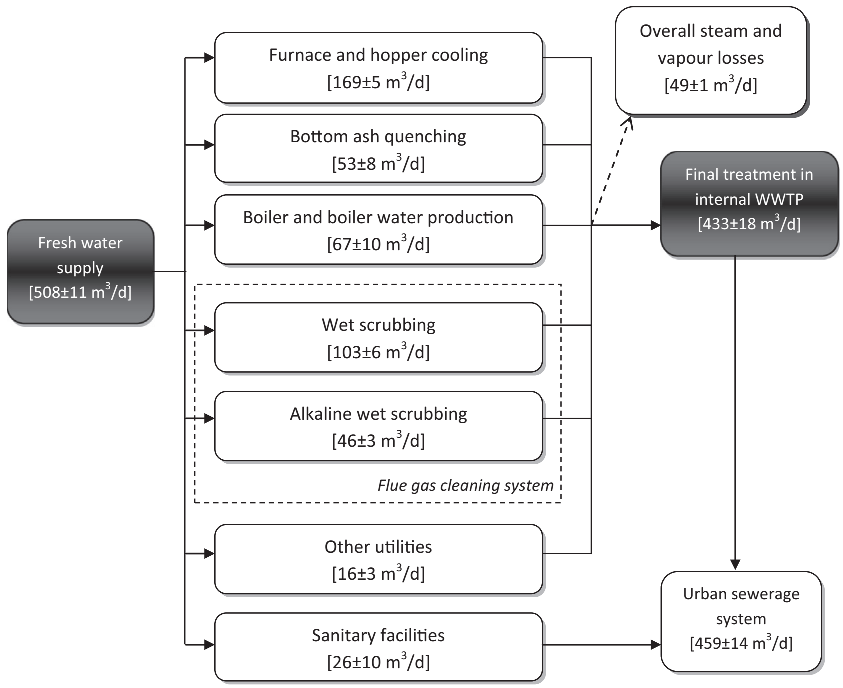

Fig. 1. Scheme of the water usage cycle in the waste-to-energy plant and measured supplied and process water flow rates (mean value ± standard deviation) by each utility.

Table 1
Physical chemical characterisation of contaminated flows (mean value ± standard deviation). Numbers in brackets represent the number of sampling days (three samples for each day).

Parameter	Unit	Fresh water	Bottom ash quenching	Alkaline wet scrubbing	Wet scrubbing	WWTP effluent
Alkalinity	mgCaCO$_3$ L^{-1}	85 ± 5 (16)	2,270 ± 350 (12)	58.9 ± 7.1 (32)	0 (16)	–
Conductivity	mS cm^{-1}	225 ± 15 (16)	14.0 ± 2.3 (48)	5.5 ± 1.8 (32)	10.9 ± 2.2 (16)	3.3 ± 1.5 (8)
Hardness	mgCaCO$_3$ L^{-1}	100 ± 10 (16)	2,100 ± 950 (12)	129 ± 12 (32)	124 ± 6 (16)	–
pH	–	8.1 ± 0.4 (16)	12.2 ± 0.2 (48)	6.2 ± 0.3 (32)	1.4 ± 0.1 (16)	8.2 ± 0.9 (36)
Susp. solids	mg L^{-1}	0 (4)	360 ± 250 (12)	5.9 ± 4.1 (8)	3.5 ± 3.0 (4)	11.6 ± 4.7 (36)
Temperature	°C	15 ± 1 (16)	35 ± 2 (48)	50 ± 1 (32)	50 ± 1 (16)	18 ± 3 (16)
Aluminium	mg L^{-1}	<0.02 (4)	16.1 ± 10.8 (12)	0.37 ± 0.14 (8)	0.91 ± 0.39 (4)	1.6 ± 0.16 (8)
Chloride	mg L^{-1}	<1 (4)	>3,000 (48)	>3,000 (32)	2,000 ± 700 (16)	317 ± 116 (16)
Chromium, tot.	mg L^{-1}	<0.004 (4)	1.87 ± 1.22 (12)	<0.004 (8)	<0.004 (4)	0.1 ± 0.1 (16)
Copper	mg L^{-1}	<0.002 (4)	1.05 ± 0.55 (12)	0.008 ± 0.002 (8)	0.008 ± 0.003 (4)	<0.002 (8)
Lead	mg L^{-1}	<0.03 (4)	1.56 ± 1.05 (12)	<0.03 (8)	<0.03 (4)	<0.03 (8)
Mercury	mg L^{-1}	<0.001 (4)	<0.001 (12)	<0.001 (8)	<0.001 (4)	<0.001 (8)
Nickel	mg L^{-1}	<0.01 (4)	0.07 ± 0.03 (12)	<0.01 (8)	<0.01 (4)	<0.01 (8)
Sulfate	mg L^{-1}	<0.1 (4)	70 ± 22 (12)	537 ± 150 (8)	<0.1 (4)	269 ± 30 (8)
Zinc	mg L^{-1}	<0.02 (4)	1.82 ± 1.07 (12)	0.05 ± 0.014 (8)	0.045 ± 0.017 (4)	0.10 ± 0.06 (16)

flow rate of 180 m^3 d^{-1} has been assumed in order to guarantee a higher dilution of the pollutants in the final discharge.

According to utility specificity and the technologies available at the present time, technical constraints can be summarised as follows:

– since the water for furnace/hopper cooling is heated and flows into pipes, scaling waters are not acceptable;
– since the water for bottom ash quenching is sprayed by nozzles, scaling waters are not admissible, and very low concentration of suspended solids is required;
– since boiler water is pre-treated with ion-exchange resins before use, and the pre-treatment is designed for potable water feeding, waters with different characteristics cannot be fed to this section of the plant without additional treatments;
– flue gas cleaning water cannot be scaling, must have low concentration of suspended solids and low concentration of any kind of pollutants that can be transferred from water to gas.

3.3. Process water reuse, without specific additional treatments (cascade configuration)

By reason of above reported constraints, there is no possibility to recover the WWTP effluent because its quality is not compatible with any utility requirements. In addition, it should be outlined that WWTP effluent can be subjected to quality changes due to malfunctioning or other unpredictable causes: a decrease in WWTP efficiency can in fact dramatically increase the concentrations of suspended solids and other pollutants in the effluent, with serious drawbacks on the functionality of the WtE plant. Besides, process water from bottom ash quenching and flue gas cleaning utilities are scaling and highly contaminated. The only flows that can be reused as such are cooling and boiler waters that are, as a matter of fact, heated potable water.

Fig. 2 represents the most efficient cascade configuration for process water reuse without additional treatments, in which cooling and boiler waters feed the bottom ash quenching and the flue

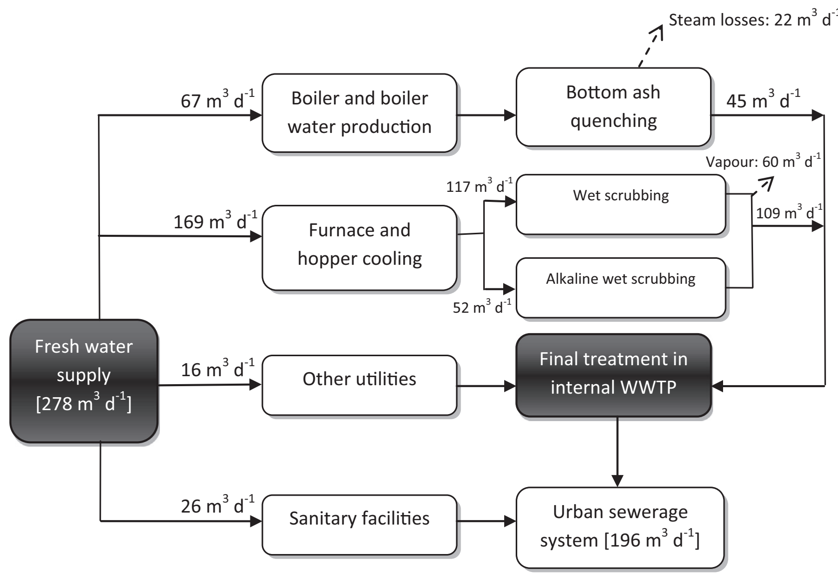

Fig. 2. Water reuse scheme, without specific additional treatments (cascade configuration).

Table 2
Temperature measured in the present configuration of the WtE plant, and calculated for both the cascade and the cascade/RO configurations.

	Present configuration (°C)	Process water reuse (°C)
Boiler and boiler water production IN	15	15
Boiler and boiler water production OUT	65	65
Boiler and boiler water production ΔT	50	50
Bottom ash quenching IN	15	65
Bottom ash quenching OUT	40	90
Bottom ash quenching ΔT	25	25
Furnace and hopper cooling IN	15	15
Furnace and hopper cooling OUT	40	40
Furnace and hopper cooling ΔT	25	25
Flue gas cleaning system IN	15	40
Flue gas cleaning system OUT	50	75
Flue gas cleaning system ΔT	35	35

gas cleaning utilities. This configuration reduces the fresh water consumption of about 45% (from 508 m^3/d to 278 m^3/d, on average).

The flow rates fed to the utilities where steam is generated are slightly higher than the actual requests, in order to compensate the higher steam losses due to the increase of water temperature. It was verified that the temperature of the reclaimed flows are suit-able for the reuse, as shown in Table 2, assuming that the increase of temperature in the various utilities in the present configuration can be maintained equal in the cascade configuration. In fact, since water remains in the liquid phase, the relationship between the heat exchanged (h) and the difference of temperature (ΔT) is linear:

$$h = c \cdot Q \cdot \rho \cdot \Delta T \qquad (2)$$

where h is the heat exchanged [J d^{-1}], c is the specific heat of water [4,186 J kg^{-1} °C^{-1}], Q is the water flow rate [m^3 d^{-1}], ρ is the density of water [1,000 kg m^{-3}] and ΔT is the difference of temperature [°C]. Therefore, the temperature of used process water will be around 75 °C at the outlet of the scrubbers and 90 °C at the end of the bottom ash quenching. These values were considered acceptable by the WtE plant managers as they do not imply any malfunctioning of the existing structures.

However, an increase of temperature can affect steam generation. The steam loss from the bottom ash quenching can be considered rather unaffected, because the steam generation is caused by the direct contact between bottom ashes and water, and the equilibrium temperature is below 100 °C. Nevertheless, as a safety factor, the value measured in the existing configuration was doubled in the cascade configuration evaluation. On the contrary, the vapour losses in the two scrubbers depend on the moisture content of treated flue gas, which is a function of temperature: considering that the atmosphere inside the scrubbers is saturated, it is possible to evaluate a steam loss of 60 m^3 d^{-1} at a temperature of 75 °C by means of a Mollier diagram.

The specific water consumption in the cascade configuration is 0.99 m^3 t_{MSW}^{-1}. The discharged flow rate is 196 m^3 d^{-1}, which is higher than the minimum admissible value (180 m^3 d^{-1}) previously defined. Thus, the maximum expected chloride and sulfate concentrations in the effluent are 1,033 mg L^{-1} and 704 mg L^{-1} respectively, both under the discharge limit.

No operational issues should occur to manage the new concentrations of metals and suspended solids, which are approximately double compared with the current ones, because the halving of the flow rates implies the doubling of the hydraulic retention time of the reactors. It is however necessary to verify if, due to the doubling of the concentrations of pollutants and the modification of the hydrodynamic conditions, the dosage of chemical reagents needs to be increased.

The cascade configuration is technically very simple and do not requires any relevant improvement of the existing facilities. In this specific case, the specific cost of potable water can be assumed between 0.35 and 0.5 € m^{-3} and the specific cost for the municipal wastewater treatment ranges from 0.9 and 1.5 € m^{-3}. Consequently, with the cascade configuration, the daily cost of water management (estimated in the last years between 550 and 900 € d^{-1}, i.e. 200,000–330,000 € y^{-1}) can be reduced of 300–400 € d^{-1} (110,000–150,000 € y^{-1}). This result shows that it is pos-sible to reduce the water consumption, and in turn the wastewater production, reducing at the same time the operating costs of the facility.

3.4. Process water reuse, with specific additional treatments (cascade and reverse osmosis configuration)

The cascade configuration has some constraints that limit its flexibility. To further increase the water usage efficiency, it is necessary to design an improved configuration in which the cascade configuration is integrated by further treating and recycling the final WWTP effluent (Fig. 3).

Since chloride and sulfate ions cannot be removed by conventional treatment processes, a more specific technology has to be adopted. Reverse osmosis (RO) is currently the most important desalination technology and it is experiencing significant growth (Lee et al., 2011; Loutatidou et al., 2014). Reverse osmosis produces a permeate flow with a very low saline concentration to be recycled in the WtE plant, and a concentrate flow with a very high saline concentration to be adequately disposed. In this configuration, fresh water is needed only to compensate steam losses and the production of concentrate in the reverse osmosis unit. As a consequence, the existent WWTP can be interpreted as first stage pretreatment of the wastewater before reverse osmosis, which needs a feed water of a specific quality. In Fig. 3, it can be observed that 131 m^3 d^{-1} of fresh water are needed (the 26% of the current water consumption), which represents a specific consumption of 0.46 m^3 t_{MSW}^{-1}. This implies a water saving of 377 m^3 d^{-1}. Nevertheless, this solution is complex and expensive because it requires the installation of a heat exchanger, a reverse osmosis section, and the additional pre-treatments (e.g. filtration, pH adjustment, biocide and antiscalant dosing, ...) and post-treatments (e.g. pH adjustment). In particular, to mix the organic effluent (san-itary facilities) with non-organic effluents could create problems on the operation of reverse osmosis, because a higher cost of maintenance will be needed. Therefore, the reuse of this particular flow should be carefully considered.

The heat exchanger is required because, in a closed loop, heat accumulates and temperature increases. Assuming data in Table 2 and flow rates in Fig. 3, the energy discharged with the WWTP effluent results in an interval between $5 \cdot 10^7$ and $6 \cdot 10^7$ kJ d^{-1}. Moreover, reverse osmosis needs to operate in a well-defined temperature range, which depends on manufacturer specifications.

It should be mentioned that incineration is a suitable way to dispose the concentrate flow of a reverse osmosis. However, the incineration of the concentrate in the same WtE plant where it is produced determines a mass loop (mainly for chloride and sulfate), because the pollutants removed by the flue gas cleaning system are brought into the system again. Incineration of the concentrate flow also implies an increase of the pollutant concentration in the various sections of the WtE plant (process water and flue gas), that should be planned carefully in order to anticipate possible malfunctioning. Therefore, the designer or the plant managers should consider this option only after an analysis of the whole WtE plant layout.

As for the reverse osmosis, it can be assumed that a well-designed process produces an amount of concentrate equal to 25% of the influent flow rate. The RO management cost per cubic meter of treated water ranges from 0.5 to 1 € m^{-3}, and the disposal of the concentrate approximately from 2 to 5 € m^{-3} in an

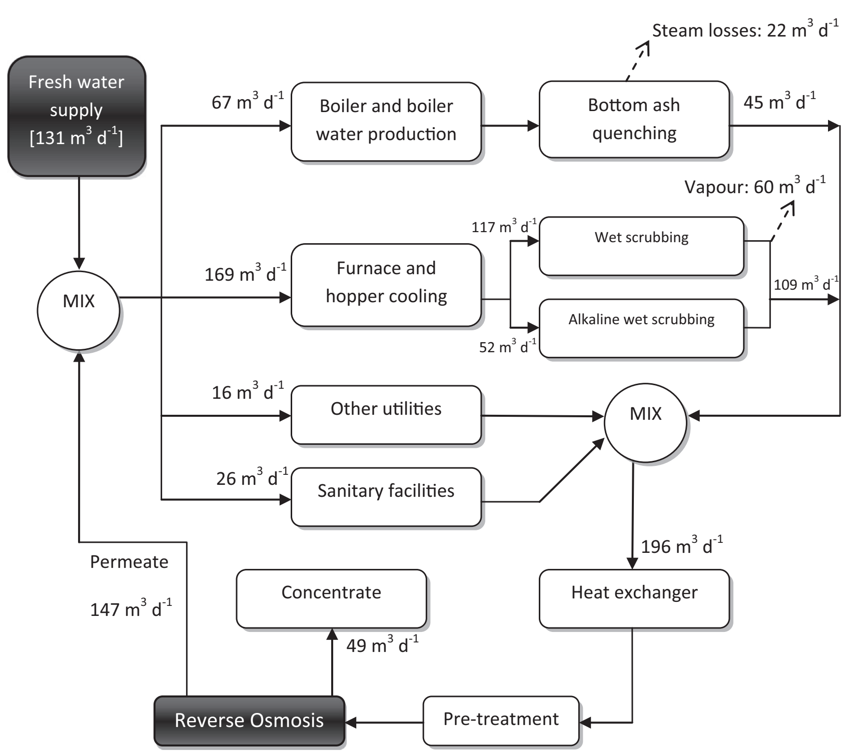

Fig. 3. Water reuse scheme, with specific additional treatments (cascade and reverse osmosis configuration).

authorised facility. Therefore, the total daily cost due to the utilisation of the reverse osmosis system can be calculated in 200–500 €, while the water consumption decrease implies an estimated reduction of the costs of 130–200 € d^{-1}. The most important aspect, from the economic point of view, is the fact that the discharge to the urban sewerage system can be virtually reduced to zero, allowing a saving of 400–650 € d^{-1}. These values do not include the installation cost of the reverse osmosis plant (approximately 200,000 €) and the cost of installation and operation of the heat exchanger (approximately 100,000 €, Italian market quotation). Assuming a lifetime of the equipment of 15 years, and a discount rate of 5–10%, it can be calculated a reasonable equipment daily cost of 90–120 €.

The system can therefore allow an overall reduction of the costs (from 80 to 150 € d^{-1}, i.e. 30,000–55,000 € y^{-1}), but it requires a relevant technical effort (the discussed balance did not consider, for example, the personal cost for operating the RO plant, the maintenance of pumps, piping, ...) and should be carefully evaluated from case to case using site-specific data.

4. Conclusions

The present paper describes a case study aimed at reducing the fresh water consumption and the related wastewater production in a waste-to-energy plant. The water cycle of an Italian WtE plant treating approximately 280 t_{MSW} d^{-1} with a specific water consumption of 1.81 m^3 t_{MSW}^{-1} was studied. In order to obtain an efficient configuration, flow rates and pollutant concentrations of every process water flow were measured and compared with the acceptability limits (quantitative and qualitative) of each process.

This allowed designing a cascade water usage configuration, without additional treatments, with a water saving efficiency of 45% with respect to the existing situation. This configuration is quite inexpensive because it does not require the installation of specific devices, and at the same time allows a significant reduction of the costs. The most important constraint in a cascade configuration is the concentration of chloride and sulfate in the final effluent, that must comply with limits for discharge into sewerage, considering that they cannot be removed by conventional water treatments. This constraint determines a minimum flow rate to be discharged, that can affect the water saving efficiency of the cascade configuration.

To further increase the water saving efficiency, overcoming the above reported constraint, a reverse osmosis system is necessary to improve the quality of the effluent of the final wastewater treatment plant, to be recycled in the WtE plant. The reclaimed WWTP effluent can partially substitute fresh water, with a saving efficiency of 74%. On the other hand, this kind of solution requires the installation of a reverse osmosis unit (included appropriate pre- and post-treatments) and of a heat exchanger. The solution is still feasible, even if the high installation and operation costs of the reverse osmosis unit limit the advantage of the drastic reduction of the production of wastewater.

The research showed that the aware knowledge of the water cycle of a WtE plant could help in the implementation of smart approaches in order to reduce both the consumption of fresh water and the production of wastewater. Moreover, the partial or total reuse of wastewater appears very interesting from an economic point of view, since both the considered scenarios could allow reducing the operating cost of the plant. Further studies should verify the feasibility of the reuse approach in different WtE operating conditions and countries, in particular in arid areas where the intrinsic value of water is high.

Acknowledgements

This research has been funded by Silea S.p.A. Authors wish to thank dott. Marco Peverelli, for having made this study possible, and dott. Gabriella Sinigaglia and Mr. Valerio Valsecchi, for their helpful cooperation during monitoring campaign and identification of water usage cycle.

References

APHA, AWWA, WEF, 2012. Standard Methods for the Examination of Water and Wastewater, 22nd ed., Water Environment Federation Publishing, Alexandria, VA, USA.

Belboom, S., Digneffe, J.-M., Renzoni, R., Germain, A., Léonard, A., 2013. Comparing technologies for municipal solid waste management using life cycle assessment methodology: a Belgian case study. Int. J. Life Cycle Ass. 18 (8), 1513–1523.

Cardoso, A.J., Levine, A.D., Rhea, L.R., 2008. Batch test assessment of waste-to-energy combustion residues impacts on precipitate formation in landfill leachate collection systems. J. Air Waste Manage. 58 (1), 19–26.

Cleary, J., 2009. Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature. Environ. Int. 35 (8), 1256–1266.

Cucchiella, F., D'Adamo, I., Gastaldi, M., 2014. Strategic municipal solid waste management: a quantitative model for Italian regions. Energ. Convers. Manage. 77, 709–720.

Deuster, E.v., Mensing, A., Jiang, M.X., Majdeski, H., 1994. Cleaning of flue gas from solid waste incinerator plants by wet/semi-dry process. Environ. Prog. 13 (2), 149–153.

Feng, S., Wang, X., Wei, G., Peng, P., Yang, Y., Cao, Z., 2007. Leachates of municipal solid waste incineration bottom ash from Macao: heavy metal concentrations and genotoxicity. Chemosphere 67, 1133–1137.

Fu, F., Wang, Q., 2011. Removal of heavy metal ions from wastewaters: a review. J. Environ. Manage. 92 (3), 407–418.

Herva, M., Roca, E., 2013. Ranking municipal solid waste treatment alternatives based on ecological footprint and multi-criteria analysis. Ecol. Indic. 25, 77–84.

Hjelmar, O., 1996. Disposal strategies for municipal solid waste incineration residues. J. Haz. Mat. 47, 345–368.

Jung, C.H., Matsuo, T., Tanaka, N., Okada, T., 2004. Metal distribution in incineration residues of municipal solid waste (MSW) in Japan. Waste Manage. 24, 381–391.

Klemeš, J.J., 2012. Industrial water recycle/reuse. Curr. Opin. Chem. Eng. 1, 238–245.

Kurniawan, T.A., Chan, G.Y.S., Lo, W.H., Babel, S., 2006. Physico-chemical treatment techniques for wastewater laden with heavy metals. Chem. Eng. J. 118 (1–2), 83–98.

Lee, K.P., Arnot, T.C., Mattia, D., 2011. A review of reverse osmosis membrane materials for desalination-development to date and future potential. J. Membr. Sci. 370, 1–22.

Loutatidou, S., Chalermthai, B., Marpu, P.R., Arafat, H.A., 2014. Capital cost estimation of RO plants: GCC countries versus southern Europe. Desalination 347, 103–111.

Ma, J.Y., Chen, X.Y., Su, W., 2014. Environmental evaluation for three typical MSW incineration based on life cycle assessment. Adv. Mat. Res. 850–851, 1360–1363.

McLarty, R., Going, V., Schauer, R., 2012. An introduction to the cascading water management system for sustainable water conservation at waste-to-energy facilities. In: 20th Annual North American Waste-to-Energy Conference, Portland, Maine, USA, April 23–25, 2012.

Metcalf, Eddy, 2003. Wastewater Engineering: Treatment and Reuse, 4th ed, revised by G. Tchobanoglous, F.L. Burton, H.D. Stensel. McGraw Hill, New York.

Mohsen, M.S., 2004. Treatment and reuse of industrial effluents: case study of a thermal power plant. Desalination 167, 75–86.

Morselli, L., Luzi, J., Robertis, C.D., Vassura, I., Carrillo, V., Passarini, F., 2007. Assessment and comparison of the environmental performances of a regional incinerator network. Waste Manage. 27, S85–S91.

Oliveira-Esquerre, K.P., Kiperstok, A., Mattos, M.C., Cohim, E., Kalid, R., Sales, E.A., Pires, V., 2011. Taking Advantage of storm and waste water retention basins as part of water use minimization in industrial sites. Resour. Conser. Recy. 55, 316–324.

Passarini, F., Nicoletti, M., Ciacci, L., Vassura, I., Morselli, L., 2014. Environmental impact assessment of a WtE plant after structural upgrade measures. Waste Manage. 34, 753–762.

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.

Sekito, T., Onoue, K., Dote, Y., Sakanakura, H., Nakamura, k., 2015. Variation and correlation of content and leachability of hazardous metals in MSW molten slag. Environ. Monit. Assess. 187 (1), 4193–4198.