Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 148 (2018) 162–169

Energy Procedia

www.elsevier.com/locate/procedia

73rd Conference of the Italian Thermal Machines Engineering Association (ATI 2018),
12–14 September 2018, Pisa, Italy

Environmental evaluation of Waste to Energy plant coupled with concentrated solar energy

Barbara Mendecka[a], Lidia Lombardi[b]*

[a] *Industrial Engineering Department, University of Florence, via Santa Marta 3, Florence 50139, Italy*
[b]*Niccolò Cusano University, via don Carlo Gnocchi 3, Rome 00166, Italy*

Abstract

Life Cycle Assessment (LCA) was applied to evaluate the environmental impact of a hybrid energy system based on the integration of a Waste to Energy plant with concentrated solar energy plant. In the Waste to Energy (WtE) section only saturated steam is produced, while the superheating takes place in an external superheater fed by the concentrated solar energy or, when this is not enough, by a natural gas backup boiler. Different couples of pressure and temperature, for the superheated steam (51 bar, 440 °C; 60 bar, 480 °C; 70 bar, 520 °C), different values for the solar multiple (1.5, 2.0 and 2.5) and different values for the thermal storage capacity (6 h, 10 h and 14 h) were considered, leading to 27 possible cases. Construction, operation and end-of-life phases were included in the LCA system boundary. Calculated global warming indicator, in kg of equivalent CO_2 per MJ of produced electricity, slightly decreases for increasing steam parameter cases and for increasing storage hour cases, while a more relevant reduction was observed for increasing solar multiple values. The main contribution to global warming derives from the operation phase of the WtE part (67-86% of the operation), while the remaining part (14-33%) is given by the solar section, for which, in turn, the main contribution is the impact deriving from the natural gas combustion in the backup boiler.

Keywords: WtE plant; concentrated solar energy; life cycle assessment; global warming

---

* Corresponding author. Tel.: +39-366-6381000.
E-mail address: lidia.lombardi@unicusano.it

10.1016/j.egypro.2018.08.045

1. Introduction

Energy recovery from waste can play a role in the present and future displacement of fossil energy [1]. Residual non-recyclable wastes – remaining downstream the application of the European Union waste hierarchy (i.e. prevention, reuse and recycling) still have valuable energy content [2]. For example, the low heating value (LHV) of the residual municipal solid waste (MSW) in EU is about 10.3 GJ/Mg [3], with about 50% share of renewable carbon content [4]. State of the art for the energy recovery from such residual waste streams is combustion with energy recovery in a conventional steam cycle, generally known as Waste-to-Energy (WtE) plant [5]. Waste combustion generates several pollutants in the flue gases and one of the main issues, due to acid gases presence and constraining the efficiency of this plants, is related to high-temperature corrosion problems [6, 7]. As a matter of fact, to limit the high-temperature corrosion problems, the WtE plants operate at quite conservative superheated steam parameters, typically 40 bar pressure and 400°C temperature [8]. Considering, also, that relatively high parasitic consumptions and other technical limitations apply, the net efficiency of the WtE plant is typically in the range 22-25 %, while maximum values of 30% can be reached only in large installations [9]. In order to remove this constraint for the maximum values of superheated steam parameters, the use of an external superheater was proposed [10]. External superheater, consisting of the natural gas-fired boiler was, for instance, installed in the WtE plant in Heringen (Germany) [11]. Alternatively, the external superheating can be realised by using concentrated solar energy. The potential benefits, in terms of increased energy production and increased efficiency, of this integrated solution, were already presented in some previous works by the authors [12, 13].

In this work, Life Cycle Assessment (LCA) is applied to evaluate the environmental impact of a hypothetical WtE plant integrated with concentrated solar energy.

Nomenclature

AC CON	Air-cooled condenser	HRSG	Heat Recovery Steam Generator
BA	Bottom ashes	LCA	Life Cycle Assessment
BGF	Boiler furnace	LP T	Low-Pressure Turbine
Cold TS	Cold storage tank	MP T	Medium Pressure Turbine
DEA	Deaerator	MSW	Municipal Solid Waste
ECON	Economizer	p	Pressure
EVAP	Evaporator	R	Receiver
FA	Fly ashes	RHEX	Regenerative heat exchanger
LHV	Low Heating Value	SM	Solar multiple
GB	Gas backup boiler	SH	Superheater
h	hours	T	Temperature
H	Heliostats	TMY	Typical Meteorological Year
Hot TS	Hots storage tank	WtE	Waste-to-Energy
HP T	High-Pressure Turbine		

2. Material and methods

The methodology applied for evaluating the environmental burdens of the hypothetical WtE plant integrated with concentrated solar energy is LCA [14, 15], so the following paragraphs report the different steps included in the methodology: goal and scope definition, inventory analysis, impact assessment.

2.1. Goal and scope definition

Definition of the goal is the first phase of the LCA, in which the purpose of the study is described. It identifies and defines the object of the assessment.

The aim of this study is to evaluate the environmental burdens – throughout the entire life cycle – of different cases of integration of concentrated solar energy into the WtE plant. The functional unit that will be used to show the results is the unit of net electricity generated by the systems, i.e. 1 MJ of generated electricity. The boundaries of the system studied in the LCA include the construction of the plants, the operation and the plant end-of-life phases.

In the following, the description of the way of integration and the main performances of the analysed cases are reported.

The conventional WtE system was modelled by EBSILON software, assuming conventional superheated steam parameters (40 bar; 400 °C). In the stand-alone case, the WtE was fed by about 135 200 t/y of MSW, with an LHV equal to 10.4 GJ/t, thus with a thermal power input of 50 MW on LHV basis. The net output power is 10.7 MW, and the efficiency is equal to 21.65% [12].

Fig. 1 depicts a schematic layout of the WtE plant integration with concentrated solar energy. The WtE model was modified accordingly. We assumed that the same amount of MSW of the standalone WtE case is fed to the grid furnace, while eliminating the superheater section from the heat recovery steam generator (HRSG), that now only produces saturated steam at the assumed pressure condition, by means of economisers and evaporators. Saturated steam is then superheated in the external heat exchanger, fed by concentrated solar thermal input (or gas boiler as better explained later). Subsequently, it is fed to the high-pressure steam turbine, and then through medium-pressure and low-pressure stages to the air-cooled condenser. Condensate from the condenser is supplied to the HRSG through the one-stage regenerative heat exchanger and deaerator.

The external superheater is fed by molten salts mixture, being the heat transfer fluid in the concentrated solar energy section. The solar field is composed of heliostats, which reflect and concentrate solar radiation on a receiver located on the upper part of a solar tower. Molten salts are pumped from a cold storage tank through the receiver, where they are heated, and then stored in the hot storage tank. Hot salts are pumped to the external heat exchanger where the steam is superheated to the design temperature, and the exiting salts are returned to the cold storage tank where they are stored.

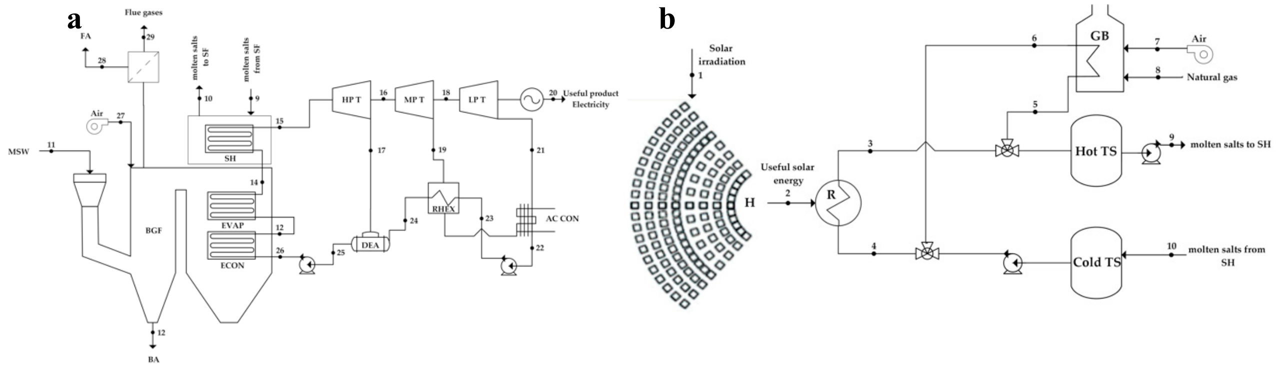

Fig. 1. (a) Structure of WtE steam cycle: MSW – municipal solid wastes, BGF – boiler furnace, ECON – economizer, EVAP – evaporator, SH – superheater, HP T – high pressure turbine, MP T – Medium pressure turbine, LP T – low pressure turbine, AC CON – air-cooled condenser, RHEX – regenerative heat exchanger, DEA – deaerator, FA – fly ashes, BA – bottom ashes. (b) Structure of solar system with heliostats and solar tower: H – heliostats, R – receiver, GB – backup gas boiler, Hot TS – hots storage tank, Cold TS – cold storage tank.

The WtE HRSG was assumed to operate at constant design parameters, producing saturated steam at the selected pressure levels. The external superheater is assumed to produce superheated steam at constant pressure and temperature (according to the different couples of selected values), too. Of course, the solar radiation is not constant during the time. Thus data for a typical year were considered in reference to a hypothetical site in the southern part of Italy (13.1 °E ; 38.2 °N). Local hourly values of direct normal irradiation, wind speed and other weather conditions for the whole year were obtained from the typical meteorological year (TMY) of Meteonorm database [13]. The assumed design point for solar field is solar noon on June 21st. The key parameters for designing are shown in Table 1.

Table 1. Design point parameters for the solar field.

Parameter	**Value**	**Parameter**	**Value**
Direct Normal Irradiance (W/m^2)	600	**Average wind speed (m/s)**	3.8
Design solar multiple	1.5-2.5	**Longitude (°)**	38.18 °N
Hours of storage at power cycle full load (h)	6-14	**Latitude (°)**	13.1 °E
Average temperature (°C)	18.8		

Table 2. Performance outputs and size parameters for the different cases of WtE integrated with concentrated solar energy. Adapted from [13].

Case no.	**Steam parameters**	**Solar Multiple/time of storage**	**Superheating power**	**Storage tank size**	**Heliostat aperture**	**Net electricity output**
	bar/°C	-/h	MW	m^3	m^2	MWh/year
1	51.0/440	1.5/6	9.8	462	59 640	123 973
2		1.5/10	9.8	713	59 640	123 973
3		1.5/14	9.8	998	59 640	123 974
4		2.0/6	9.8	571	79 440	123 998
5		2.0/10	9.8	951	79 440	124 007
6		2.0/14	9.8	1 331	79 440	124 008
7		2.5/6	9.8	713	99 240	124 013
8		2.5/10	9.8	1 189	99 240	124 026
9		2.5/14	9.8	1 664	99 240	124 030
10	60.0/480	1.5/6	11.7	510	70 920	133 993
11		1.5/10	11.7	882	70 920	133 994
12		1.5/14	11.7	1 235	70 920	133 994
13		2.0/6	11.7	705	94 560	134 022
14		2.0/10	11.7	1 176	94 560	134 033
15		2.0/14	11.7	1 646	94 560	134 035
16		2.5/6	11.7	882	118 200	134 039
17		2.5/10	11.7	1 470	118 200	134 057
18		2.5/14	11.7	2 058	118 200	134 062
19	70.0/520	1.5/6	13.6	619	83 040	144 581
20		1.5/10	13.6	1 073	83 040	144 582
21		1.5/14	13.6	1 502	83 040	144 582
22		2.0/6	13.6	858	110 640	144 616
23		2.0/10	13.6	1 430	110 640	144 628
24		2.0/14	13.6	2 002	110 640	144 630
25		2.5/6	13.6	1 073	138 360	144 636
26		2.5/10	13.6	1 788	138 360	144 654
27		2.5/14	13.6	2 503	138 360	144 662

When the solar radiation input is not enough, first the discharge of the molten salt storage tanks and then the use of a natural gas (LHV equal to 47.9 GJ/t) backup boiler (when the hot storage tank level is below 10%) operations were considered, in order to keep constant production of superheated steam at the design pressure and temperature. When the solar radiation is in excess, it is used to charge the molten salt storage tanks: when the hot storage tank level is above 90%, the part of solar energy available at the receiver is dumped, e.g., by means of heliostat defocusing. Of course, the applied control strategy has the aim of minimising the backup gas consumption.

For the analysis, different operating conditions, mainly superheated steam parameters (pressure and temperature) were previously simulated and investigated by the authors [13]. In particular different couples of pressure and temperature, for the integrated system, were considered: 51 bar and 440 °C; 60 bar and 480 °C and 70 bar and 520 °C. It should be reminded that the upper limit for the superheated steam temperature equal to 520 °C, is imposed by the maximum temperature allowable for the molten salts, which is 565 °C at maximum. Similarly, since the salts solidify at 290 °C, we need to assume a temperature difference between the temperature of the salts and the saturated steam one of at least 25 °C, which corresponds to a saturation temperature value of about to 265°C, on turn corresponding to a minimum saturation pressure of 51 bar (assumed for the superheated steam pressure too). As in [13], the values assumed for the solar multiples (SM) are 1.5, 2.0 and 2.5, while the assumed values for the thermal storage capacity (full load heat source) were 6 h, 10 h and 14 h. The two parameters strongly influence the estimated solar field extension. The combination of the three different steam parameters, SM values and thermal storage capacities led to 27 layouts.

Table 2 reports the performance data for the analysed 27 cases of integration of WtE and concentrated solar energy section.

2.2. Inventory

In this LCA phase, all the inputs and outputs occurring in the life cycle of the system previously defined are inventoried to perform a quantitative description of all flows of materials and energy across the system boundary, either into or out of the system itself.

Inventory data are gained by modelling the processes and by using literature data. Details are given in the following paragraphs for each process included within the system boundary, mainly distinguishing them into construction, operation and end-of-life.

For the construction of the plant, data were retrieved from literature. Table 3 reports the amount of main materials included in the construction phase, distinguishing between the WtE part and solar part. For the WtE part, the amount of construction materials changes according to the levels of the saturated steam pressure, while the amount of waste input remains constant. The amount of construction materials of the solar part changes as heliostat area and storage tanks change for each case. For conciseness reason, Table 3 reports the range of the amount of materials calculated for the 27 cases.

Table 3. Main materials and consumptions considered for the construction phase. The range of values refers to the different values obtained for the different 27 cases.

Construction of WtE part			**Construction of solar part**		
Aluminium, wrought alloy	t	37 625 - 53 130	Aluminium, wrought alloy	t	1 910 – 3 760
Copper	t	36 060 - 50 921	Copper	t	11 415 – 22 585
Steel, low alloyed, unalloyed, stainless	t	2 179 960–2 666 200	Steel, low alloyed, unalloyed, stainless	t	2 325 205–3 686 295
Concrete block	t	16 107 080–22 744 590	Concrete block	t	61 674 920–109 231 505
Gravel, crushed	t	39 905 - 56 350	Gravel, crushed	t	2 919 130 – 6 253 910
Glass fibre reinforced plastic	t	18 530 - 26 165	Flat glass, coated	t	629 750 – 1 349 160
Rock wool	t	11 400 - 16 100	Glass fibre reinforced plastic	t	30 770 – 65 150
Energy consumption for solar part construction			Rock wool	t	78 905 – 186 270
Diesel, burned in building machine	T	1 319 870 – 2 827 670	Molten salts (60% $NaNO_3$ and 40% KNO_3)	t	917 – 4 505
Electricity, medium voltage	MWh	296 970 – 636 225			

Operation phase includes (Table 4): consumption of natural gas for the backup boiler (including production processes of natural gases and emissions from its combustion); consumption of water for heliostat cleaning;

treatment of wastewater from heliostat cleaning; treatment/disposal of bottom ash and fly ash (including air pollution control residues); consumption of reactants for the air pollution control processes; waste combustion emissions (non-biogenic CO_2 contribution). The transportation of waste was also included. In particular, it was assumed a transportation distance of 50 km for the entering MSW, and a transportation distance of 20 km for the generated waste (bottom ash, fly ash and air pollution control residues).

For the end-of-life phase, it was assumed that some materials obtained from the plant dismantling, in particular, glass, plastic, concrete and metals (aluminium, steel, copper), can be partially recycled. While other materials as lubricating oil and salts are entirely disposed of.

Inventory data for chemicals production, electricity production, water production, wastewater treatment, landfill, etc. were retrieved from the Ecoinvent database [16].

Table 4. Consumptions and waste generation on an annual basis. Ranges are reported for amounts changing with the 27 cases.

Natural gas	Nm^3/year	3 159 133 – 7 258 769	Air pollution control residues	t/y	1 214
Water	m^3/year	37 384 – 87 166	Sodium bicarbonate	t/y	1 577
Wastewater	m^3/year	37 384 – 87 166	Activated carbon	t/y	79
Fly ash	t/y	4 923	Ammonia	t/y	61
Bottom ash	t/y	20 297	Non-biogenic CO_2 emissions	t/y	146 951 – 160 518

3. Results – Impact assessment

Environmental results are presented according to the Life Cycle Impact Assessment. This study is specifically based on a well-established midpoint methodology - the CML-IA baseline V3.02 / EU25 method - developed by the Institute of Environmental Sciences of the Leiden University, in the Netherlands [17]. The CML method impact assessment considers several indicators. In this paper, the results are reported only for global warming indicator, for conciseness reasons.

Fig. 2 reports the comparison of global warming indicator values per functional unit (i.e. in kg of equivalent CO_2 per MJ of produced electricity) for the 27 cases, and also for the WtE stand-alone plant reference case.

First of all, if we compare cases at different superheated steam pressure and temperature levels, but with the same SM and storage time, the calculated global warming values are slightly different, with slightly decreasing values for increasing superheated steam parameters. For example, comparing case 1 (p=51 bar; T=440°C; SM=1.5; h=6), case 10 (p=60 bar; T=480°C; SM=1.5; h=6) and case 19 (p=70 bar; T=520°C; SM=1.5; h=6), values are respectively 0.212, 0.207 and 0.201 kg of equivalent CO_2 per MJ of produced electricity, with a progressive reduction of 2.5% and 2.8%.

Similarly, we notice a very small decrease in global warming values when – keeping constant all the other parameters – we consider cases with increased storage time. Additionally, we can see that the reduction is a little bit higher in the cases with higher SM. For instance, considering the cases 13, 14 and 15 (p=60 bar; T=480°C; SM=2) the global warming values are respectively 0.1937, 0.1911 and 0.1909 kg of equivalent CO_2 per MJ of produced electricity, with a progressive reduction of 1.3% and 1.4%. While for the cases 16, 17 and 18 (p=60 bar; T=480°C; SM=2.5) the global warming values are respectively 0.184, 0.180 and 0.179 kg of equivalent CO_2 per MJ of produced electricity, with a progressive reduction of 2.2% and 2.8%.

The increase of the SM, keeping constant the other parameters, seems to provide the highest benefits in terms of global warming reduction. For example, if we consider the cases 10, 13 and 16 (p=60 bar; T=480°C; h=6), the global warming values are respectively 0.207, 0.1937 and 0.184 kg of equivalent CO_2 per MJ of produced electricity, with a progressive reduction of 6% and 11%.

From values and trends in Fig. 2, we can say that, if the aim is to reduce the global warming, it is more effective to increase the SM. However, a slight decrease is also observed when the steam parameters and the storage hours are increased.

The specific global warming of the analyzed cases of integration is generally lower than the value calculated for the stand-alone WtE base case (black column in Fig. 2), with the exception of cases 1, 2 and 3 for which that values are almost the same of stand-alone case (respectively in kg of equivalent CO_2 per MJ of produced electricity 0.212, 0.211 and 0.211 vs 0.211 of stand-alone WtE).

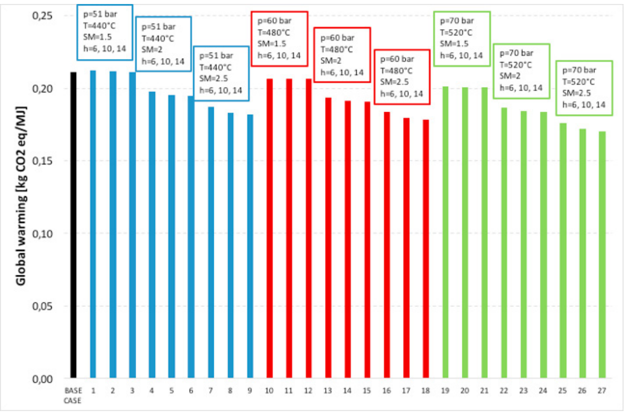

Fig. 2. Results for the global warming indicator reported with respect to the functional unit of 1 MJ of produced electricity. (p=superheated steam pressure; T=superheated steam temperature; SM=solar multiple; h=storage hours).

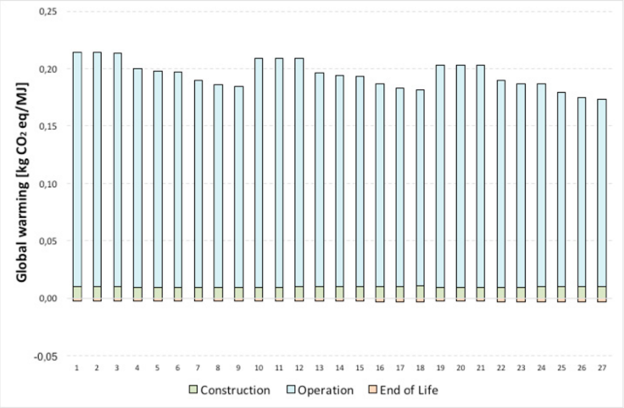

Fig. 3. Contributions to the global warming indicator reported with respect to the functional unit of 1 MJ of produced electricity, by each phase included in the life cycle.

Fig. 3 shows the contributions to global warming of the different phases included in the life cycle: construction, operation and end-of-life. The operation phase is the dominant one, while the construction and end-of-life give less relevant contributions. Construction contribution slightly increases for increasing steam parameters, increasing SM and increasing storage hours.

Concerning the operation phase, the main contribution is given by the WtE part (67-86% of the operation), while the remaining part (14-33%) is given by the solar section, for which, in turn, the main contributor to global warming derives from the natural gas combustion in the backup boiler (97-99% of the solar part operation phase). For this reason, the contribution of the operation phase decreases when SM and storage hours increase.

4. Conclusions

Life Cycle Assessment was applied to evaluate an environmental load of a hypothetical Waste to Energy plant integrated with concentrated solar energy. While the Waste to Energy section is used to produce only saturated steam (constant conditions and flow rate assured by constant thermal input by waste), the thermal power obtained from the concentrated solar energy section is used to superheat such steam. The design conditions at this external superheater (superheated steam flow rate and parameters) are maintained constant by solar energy storage strategy and by the use of a natural gas backup boiler, when necessary. Different couples of pressure and temperature, for the superheated steam (51 bar, 440 °C; 60 bar, 480 °C; 70 bar, 520 °C), different values for the solar multiple (1.5, 2.0 and 2.5) and different values for the thermal storage capacity (6 h, 10 h and 14 h) were considered, leading to 27 possible cases. Calculated global warming indicator, in kg of equivalent CO_2 per MJ of produced electricity, slightly decreases for increasing steam parameter cases and for increasing storage hour cases, while a more relevant reduction is observed for increasing solar multiple values. Thus, with the aim to reduce the global warming, it is more effective to increase the SM. The main contribution to global warming derives from the operation phase of the WtE part (67-86% of the operation), while the remaining part (14-33%) is given by the solar section. For the solar section operation, the main contributor to global warming comes from the natural gas combustion in the backup boiler. Thus, to reduce global warming indicator for the integrated system, the design should be done according to highest solar multiple values and highest storage hours, hence reducing the natural gas backup consumption.

References

[1] Rocco M. V., Di Lucchio A. and Colombo E.. "Exergy Life Cycle Assessment of electricity production from Waste-to-Energy technology: A Hybrid Input-Output approach" *Appl. Energy*, 194 (2017): 832–844, doi:10.1016/j.apenergy.2016.11.059

[2] Zhang D., Huang G., Xu Y. and Gong Q.. "Waste-to-energy in China: Key challenges and opportunities" *Energies*, 8 (12) (2015):14182–14196, doi:10.3390/en81212422

[3] Reimann D. O.. "CEWEP Energy Report III (Status 2007-2010)" no. December, pp. 1–35, 2013.

[4] Palstra S. W. L. and Meijer H. A. J.. "Carbon-14 based determination of the biogenic fraction of industrial CO_2 emissions - Application and validation" *Bioresour. Technol.*(2010), doi:10.1016/j.biortech.2009.12.004

[5] Eriksson O. and Finnveden G.. "Energy Recovery from Waste Incineration—The Importance of Technology Data and System Boundaries on CO_2 Emissions" *Energies* (2017), doi:10.3390/en10040539

[6] Lee S.-H., Themelis N. J. and Castaldi M. J.. "High-Temperature Corrosion in Waste-to-Energy Boilers" *J. Therm. Spray Technol.*, 16 (1) (2007): 104–110, doi:10.1007/s11666-006-9005-4

[7] Persson K., Broström M., Carlsson J., Nordin A. and Backman R.. "High temperature corrosion in a 65 MW waste to energy plant" *Fuel Process. Technol.*, 88 (11–12) (2007): 1178–1182, doi:10.1016/j.fuproc.2007.06.031

[8] Martin J. J. E., Koralewska R. and Wohlleben A.. "Advanced solutions in combustion-based WtE technologies" *Waste Manag.*, 37 (2015): 147–156, doi:10.1016/j.wasman.2014.08.026

[9] Lombardi L., Carnevale E. and Corti A.. "A review of technologies and performances of thermal treatment systems for energy recovery from waste" *Waste Manag.*, 37 (2015): 26–44, doi:10.1016/j.wasman.2014.11.010

[10] Consonni S. and Silva P.. "Off-design performance of integrated waste-to-energy, combined cycle plants" *Appl. Therm. Eng.*, 27(4) (2007): 712–721, doi:10.1016/j.applthermaleng.2006.10.014

[11] Main A. and Maghon T.. "Concepts and Experiences for Higher Plant Efficiency With Modern Advanced Boiler and Incineration Technology" 18th Annual North American Waste-to-Energy Conference Orlando, Florida, USA, May 11–13, 2010, pp. 33–40. doi:10.1115/NAWTEC18-3541

[12] Lombardi L., Mendecka B. and Carnevale E.. "WtE efficiency improvements: integration with solar thermal energy" in Proceedings of 5th International Conference on Sustainable Solid Waste Management. Athens, 21–24 June 2017.

[13] Mendecka B., Lombardi L., Gładysz P. and Stanek W.. "Exergo-Ecological Assessment of Waste to Energy Plants Supported by Solar Energy" *Energies* 11 (4) (2018):773, doi:10.3390/en11040773

[14] ISO (2006a). ISO 14040: Environmental management: Life-cycle assessment: Principles and framework. International Organization for Standardization, Geneva, Switzerland. Available at http://www.iso.org.

[15] ISO (2006b). ISO 14044: Environmental management: Life-cycle assessment: Requirements and guidelines. International Organization for Standardization, Geneva, Switzerland. Available at http://www.iso.org.

[16] Weidema B.P., Bauer Ch., Hischier R., Mutel Ch., Nemecek T., Reinhard J., Vadenbo C.O., Wernet G., 2013, "The ecoinvent database: Overview and methodology, Data quality guideline for the ecoinvent database version 3", www.ecoinvent.org.

[17] Guinee J. B.. "Handbook on life cycle assessment. Operational guide to the ISO standards" Springer Netherlands, 2002. doi:10.1007/0-306-48055-7