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Fuel Savings and Reduction of Greenhouse Gases in a Large Waste-to-Energy Cogeneration Facility

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Abstract

We present and discuss performance data obtained as part of the acceptance tests of a new large-scale waste-to-energy (WTE) facility recently placed in service in Brescia, Italy. We also estimate the contribution of this facility to the reduction of greenhouse gases with respect to waste landfills.

1 Introduction

A large-scale state-of-the-art-techonlogy waste-to-energy (WTE) facility has been recently placed in service in Brescia, Italy. It is part of the integrated waste management plan of the city and county of Brescia where a 35% recycling goal has already been achieved within the city. It is also part of the city's district heating (DH) system (the oldest, largest and most advanced in Italy) which in 1998 served 31 Mm^3 of heated space (almost 85% of the overall volume of buildings in the city, over 8750 homes and businesses) with 1100 GWh of thermal energy, of which about 22% from the new WTE facility.

The facility is powered by combustion of household municipal solid waste (MSW) and equivalent industrial waste. In the next future also various kind of biomasses will be mixed with MSW.

The WTE facility is equipped with two independent waste combustion groups (a third group will be added in the next future). At full load, each group produces 104 t/h of superheated steam at 60 bar and 450°C by incinerating waste with lower heating value between 1800 and 3300 kcal/kg at a load capacity between 42 t/h and 23 t/h, respectively. The steam from the two (three) groups is supplied to a single 19-stage turbine connected to three heat exchangers and a cooling tower that can operate in a variety of energy conversion configurations ranging from heat-only production (complete turbine by-pass, 162 MW at full load) to electricity-only production (52 MW at full load) to various degrees of cogeneration of electricity and heat supplied to the district heating system at temperatures in the range from 70°C to 110°C.

Data for seven acceptance-test configurations are given in Table 1 for both full load and overload conditions together with all the other parameters discussed in the article.

The facility is highly automated and instrumented. It adopts:

- Martin technology for:
  - the reverse reciprocating stoker grates on which trash is burned, combustion air supply and control, and
  - for NO_x selected noncatalytic control reduction (SNCR) through ammonia injection into the hot flue gases;
- Ansaldo technology for:
  - the boilers, superheaters, economizers, feed water heaters and piping of the two independent waste incineration groups, and
  - the turbine, generator, condensers and heat exchangers shared by the two grups;
- ABB Fläkt technology for emission control by:
  - neutralization of acid-forming compounds through powdered slaked lime injection into the exhaust flue gases at 140°C,
  - adsorption of heavy metal particulate, dioxins and furans through powdered activated carbon injection into the exhaust flue gases, and
  - high-efficiency baghouse filters.

Stack emissions are well below European standards; in particular, dust emissions are about 100 times lower than the current 10 mg/Nm^3 standard.

During the first year of operation, the average lower heating value (LHV) of the MSW has been about 2200 kcal/kg (about 4000 BTU/lb).

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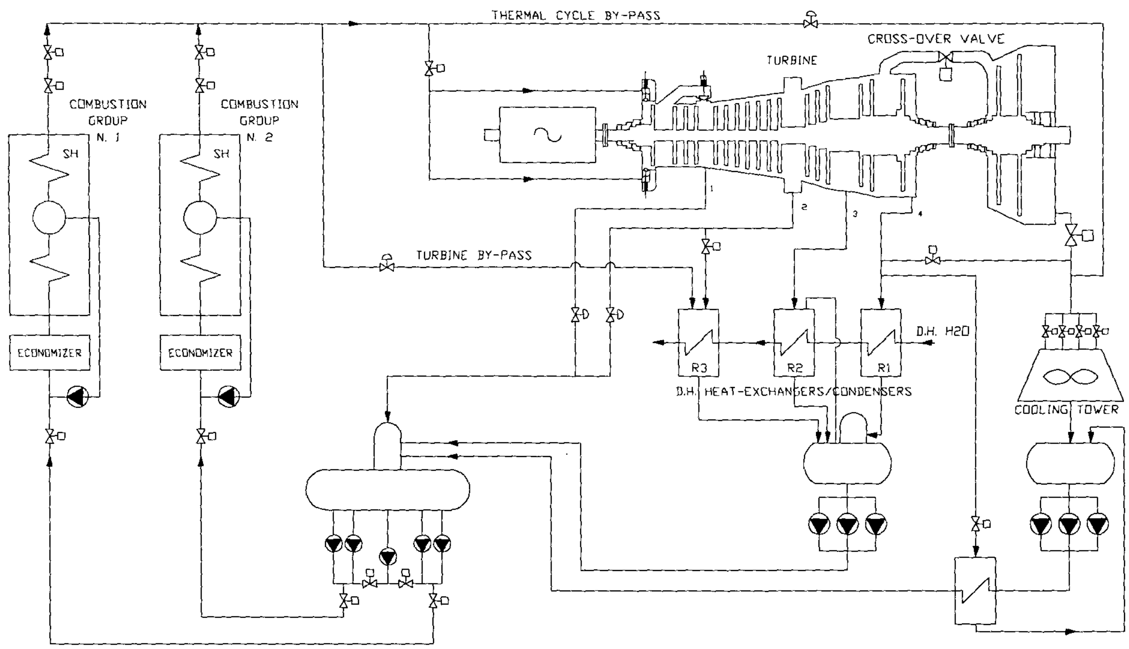

Fig. 1: Schematic diagram of the thermal cycle of the Brescia waste-to-energy facility.

2 Effectiveness of energy recovery

The thermal cycle is designed to allow high flexibility of cogeneration configurations so as to follow as much as possible electricity and heat demand along their daily and seasonal variations. Figure 1 shows a schematic diagram of the turbine configuration and the thermal cycle. Superheated vapor is supplied to the turbine from the two (three, in the near future) independent trash combustion groups. The electricity to heat production ratio is regulated by means of the cross-over valve which regulates the flow rate to the last two low-pressure turbine stages; the district-heating water feed temperature depends on the DH water mass flow rate through the three heat-exchangers/condensers R1, R2 and R3.

We report performance data on seven different acceptance-test configurations, denoted A1, A2, ..., A7. Configurations A1, A2 and A3 maximize heat production with different district-heating water feed temperatures with both combustion groups on line; A4 does the same with a single combustion group on line; A5 is a mixed production configuration with both combustion groups on line; A6 maximizes electricity-only production with both combustion groups on line and A7 does the same with a single combustion group on line. For each configuration, data are given for the full (100%) load condition as well as for the 115% overload condition that can be maintained for up to three hours a day.

2.1 Definition of effectiveness

Often, the energy efficiency of a waste-to-energy plant is reported in terms of the first-law efficiency, defined as the ratio of the sum of net electric power $\dot{W}_{\mathrm{E,\,net}}$ and district-heating thermal power $\dot{Q}_{\mathrm{DH}}$ to the thermal power from waste incineration, i.e.,

$$\eta' = \frac{\dot{W}_{\mathrm{E,\,net}} + \dot{Q}_{\mathrm{DH}}}{\dot{m}_{\mathrm{W}}\,\mathrm{LHV}}$$

where $\dot{m}_{\mathrm{W}}$ is the mass rate of waste incineration and LHV the average lower heating value of the waste. For the Brescia waste-to-energy facility, η' ranges from 26.5% to 89.4% (see Figure 2 and Table 1).

It is well known, however (see e.g. [1, 2]), that for a cogeneration plant it is thermodynamically more correct to refer to the second law efficiency or effectiveness, which takes into account properly the fact that 1 kWh of electricity is worth more than 1 kWh of hot water at a given temperature difference, $T_{\mathrm{feed}} - T_{\mathrm{env}}$, from the environmental temperature T_{env}, which in turn is worth more than 1 kWh of hot water at a lower temperature difference from T_{env}. The second law efficiency is

$$\eta'' = \frac{\dot{W}_{\mathrm{E,\,net}} + \dot{Q}_{\mathrm{DH}}\left(1 - T_{\mathrm{env}}\dfrac{\ln\left(T_{\mathrm{feed}}/T_{\mathrm{ret}}\right)}{T_{\mathrm{feed}} - T_{\mathrm{ret}}}\right)}{\dot{m}_{\mathrm{W}}\,\mathrm{LHV}}$$

where T_{ret} is the return temperature of the district heating water. For the Brescia waste-to-energy facility, η'' ranges from 26.5% to 38.5% (see Figure 2 and Table 1).

		A1		A2		A3		A4		A5		A6		A7	
Configuration		**cogeneration**								**mixed**		**electricity only**			
Combustion groups on line		2 groups		2 groups		2 groups		1 group		2 groups		2 groups		1 group	
Load condition		full load	over-load	full load	over-load	full load	over-load	full load	over-load	full load	over-load	full load	over-load	full load	over-load
Mass rate of MSW, m_W	t_{MSW}/h	66.4	86.2	66.5	82.7	65.2	76.3	38.6	43.8	65.8	86.3	71.0	74.4	37.6	46.5
Lower heating value of MSW, LHV	kcal/kg	2308	2096	2297	2148	2373	2385	2071	2088	2314	2122	2116	2403	2182	1973
Thermal power, m_W LHV from MSW incineration	MW	178.3	210.1	177.7	206.5	180.1	211.7	92.9	106.5	177.1	213.1	174.7	207.8	95.4	106.8
Thermal power to the turbine thermal cycle	MW	163.1	194.3	162.6	190.8	166.4	198.3	77.6	96.6	162.6	195.3	161.3	194.3	75.8	96.2
Fraction of incineration energy to the thermal cycle	%	91.5	92.5	91.5	92.4	92.4	93.6	83.6	90.8	91.8	91.7	92.3	93.5	79.4	90.1
Vapor to the turbine: Mass flow rate	t/h	209.9	250.2	208.9	245.6	213.4	255.4	99.8	124.3	209.0	251.4	207.2	250.2	97.4	123.7
Vapor to the turbine: Pressure	ata	58.5	59.9	58.5	59.7	58.6	59.9	59.3	59.9	58.6	59.9	58.5	59.8	58.6	59.9
Vapor to the turbine: Temperature	°C	446.6	447.5	448.4	447.7	447.7	448.1	447.3	447.2	448.4	448.0	447.8	447.5	448.3	447.8
Net electric power, W_E (high voltage grid)	MW	46.9	54.3	44.6	50.6	39.8	46.2	22.0	25.9	49.7	58.8	51.3	59.3	25.3	29.7
Net thermal power, Q_{DH} (district heating)	MW	111.1	133.5	109.8	129.0	107.7	115.5	55.3	64.1	58.2	70.6	0.0	0.0	0.0	0.0
Hot water to district heating: Mass flow rate	t/h	5918	5916	3987	4228	1843	1820	3018	2983	2973	2948	0	0	0	0
Hot water to district heating: Return temperature	°C	54.9	54.9	59.1	58.6	59.3	60.2	54.5	54.2	54.4	55.0	*	*	*	*
Hot water to district heating: Feed temperature	°C	70.9	74.2	82.6	84.7	109.4	114.6	70.1	72.6	71.1	75.4	*	*	*	*
Environmental temperature	°C	5.4	-2.6	5.1	2.6	5.3	5.7	7.7	4.3	1.8	-1.6	6.1	10.6	7.9	6.3
Cogeneration index, I_{en}	%	71.9	72.3	68.9	68.4	60.8	54.4	63.6	65.6	42.5	41.9	8.6	7.0	2.9	5.6
Electricity-only efficiency, η_{EE}	%	26.3	25.9	25.1	24.5	22.1	21.8	23.7	24.3	28.1	27.6	29.4	28.6	26.5	27.8
First law efficiency, η'	%	88.7	89.4	86.9	86.9	81.9	76.3	83.2	84.5	60.9	60.7	29.4	28.6	26.5	27.8
Second law efficiency, η''	%	37.0	38.5	36.9	37.0	35.3	34.1	33.4	34.9	34.0	34.1	29.4	28.6	26.5	27.8
Second law efficiency of η_E=0.40/η_Q=0.80 separate production	%	25.7	26.7	26.4	26.6	27.1	27.8	25.0	25.6	30.6	30.9	40.0	40.0	40.0	40.0
Second law efficiency of η_E=0.40/η_Q=0.95 separate production	%	28.1	29.2	28.9	29.1	29.8	30.5	27.4	28.1	32.5	32.9	40.0	40.0	40.0	40.0
Fuel savings with respect to: separate production with η_E=0.40 η_Q=0.80	tep/h	22.0	26.0	21.4	24.7	20.1	22.3	10.7	12.5	16.9	20.2	11.0	12.8	5.4	6.4
Fuel savings with respect to: separate production with η_E=0.40 η_Q=0.95	tep/h	20.1	23.8	19.5	22.5	18.3	20.4	9.7	11.4	16.0	19.0	11.0	12.8	5.4	6.4
Fuel savings with respect to: main Brescia cogeneration facility	tep/h	15.0	17.7	14.5	16.8	13.7	15.2	7.3	8.5	11.5	13.8	7.5	8.7	3.7	4.3
Fuel savings per ton of MSW with LHV 2200 with respect to: separate production with η_E=0.40 η_Q=0.80	tep/$t_{MSW2200}$	0.316	0.317	0.308	0.306	0.286	0.270	0.294	0.299	0.245	0.243	0.162	0.157	0.146	0.153
Fuel savings per ton of MSW with LHV 2200 with respect to: separate production with η_E=0.40 η_Q=0.95	tep/$t_{MSW2200}$	0.289	0.289	0.281	0.279	0.260	0.246	0.268	0.273	0.230	0.228	0.162	0.157	0.146	0.153
Fuel savings per ton of MSW with LHV 2200 with respect to: main Brescia cogeneration facility	tep/$t_{MSW2200}$	0.215	0.216	0.209	0.208	0.195	0.184	0.200	0.204	0.166	0.165	0.110	0.107	0.099	0.104
Reduction of greenhouse gases per ton of MSW with LHV 2200 with respect to: high tech landfill and η_E=0.40/η_Q=0.80 sep.prod.	$t_{CO2}/t_{MSW2200}$	0.73	0.72	0.70	0.69	0.63	0.59	0.66	0.68	0.56	0.56	0.37	0.36	0.32	0.34
Reduction of greenhouse gases per ton of MSW with LHV 2200 with respect to: high tech landfill and η_E=0.40/η_Q=0.95 sep.prod.	$t_{CO2}/t_{MSW2200}$	0.66	0.66	0.64	0.63	0.57	0.54	0.60	0.61	0.53	0.52	0.37	0.36	0.32	0.34
Reduction of greenhouse gases per ton of MSW with LHV 2200 with respect to: high tech landfill and main cogeneration facility	$t_{CO2}/t_{MSW2200}$	0.64	0.64	0.62	0.61	0.56	0.52	0.58	0.60	0.50	0.49	0.32	0.31	0.27	0.30
Reduction of greenhouse gases per ton of MSW with LHV 2200 with respect to: medium tech landfill and η_E=0.40/η_Q=0.80 sep.prod.	$t_{CO2}/t_{MSW2200}$	1.01	1.01	0.99	0.98	0.92	0.88	0.94	0.96	0.85	0.84	0.66	0.64	0.60	0.63
Reduction of greenhouse gases per ton of MSW with LHV 2200 with respect to: medium tech landfill and η_E=0.40/η_Q=0.95 sep.prod.	$t_{CO2}/t_{MSW2200}$	0.95	0.94	0.92	0.91	0.86	0.82	0.88	0.90	0.82	0.81	0.66	0.64	0.60	0.63
Reduction of greenhouse gases per ton of MSW with LHV 2200 with respect to: medium tech landfill and main cogeneration facility	$t_{CO2}/t_{MSW2200}$	0.93	0.93	0.91	0.90	0.84	0.81	0.87	0.88	0.78	0.78	0.61	0.59	0.56	0.58
Reduction of greenhouse gases per ton of MSW with LHV 2200 with respect to: low tech or bare landfill and η_E=0.40/η_Q=0.80 sep.prod.	$t_{CO2}/t_{MSW2200}$	3.09	3.09	3.06	3.05	2.99	2.95	3.02	3.04	2.93	2.92	2.73	2.72	2.68	2.70
Reduction of greenhouse gases per ton of MSW with LHV 2200 with respect to: low tech or bare landfill and η_E=0.40/η_Q=0.95 sep.prod.	$t_{CO2}/t_{MSW2200}$	3.02	3.02	3.00	2.99	2.93	2.90	2.96	2.97	2.89	2.88	2.73	2.72	2.68	2.70
Reduction of greenhouse gases per ton of MSW with LHV 2200 with respect to: low tech or bare landfill and main cogeneration facility	$t_{CO2}/t_{MSW2200}$	3.01	3.01	2.98	2.98	2.92	2.88	2.95	2.96	2.86	2.85	2.68	2.67	2.64	2.66

Table 1: Data on the main configurations of the Brescia waste-to-energy facility.

Italian legislation[3] recognizes in a simplified matter the different values of electricity and heat by defining an energy savings indicator as follows

$$\mathrm{I_{en}} = \frac{\dot{W}_{\mathrm{E,net}}}{0.51\,\dot{m}_{\mathrm{W}}\,\mathrm{LHV}} + \frac{\dot{Q}_{\mathrm{DH}}}{0.9\,\dot{m}_{\mathrm{W}}\,\mathrm{LHV}} - 0.49$$

which weighs electricity and heat based on the ratio 0.9/0.51 independently of the temperature at which heat is produced. Nevertheless, $\mathrm{I_{en}}$ is a useful indicator of the degree of cogeneration achieved in the fourteen configurations that we discuss (seven at full load and seven at overload conditions). For the Brescia WTE facility, $\mathrm{I_{en}}$ ranges from 2.9% to 72.3% (see Figures).

Table 1 shows values of these and other parameters for all the configurations considered. Among the other parameters, we show the values of the electricity-only efficiency

$$\eta_{\mathrm{EE}} = \frac{\dot{W}_{\mathrm{E,net}}}{\dot{m}_{\mathrm{W}}\,\mathrm{LHV}}$$

which ranges from 21.8% to 29.4%, and the fraction of thermal energy from waste incineration that reaches the thermal cycle

$$f_v = \frac{\dot{m}_v\,(h_{\mathrm{in}} - h_{\mathrm{out}})}{\dot{m}_{\mathrm{W}}\,\mathrm{LHV}}$$

which ranges from 91.5% to 92.4% at full load and from 91.7% to 93.6% at overload when both combustion groups are on line or from 79.4% to 83.6% at full load and from 90.1% to 90.8% at overload when only one group is on line, where h_{in} and h_{out} denote H_2O enthalpy into and out of the thermal cycle.

The values of LHV have been computed through detailed energy balances and analyses of several relevant on-line measurements for each of the configurations discussed.

3 Fuel savings with respect to separate production and cogeneration

It is well known that cogeneration generally saves fuel with respect to separate production of the same amount of electricity and heat. Table 1 shows values of the second law efficiency of separate production defined as follows

$$\eta''_{\mathrm{sep.prod.}} = \frac{\dot{W}_{\mathrm{E,net}} + \dot{Q}_{\mathrm{DH}}\left(1 - T_{\mathrm{env}}\dfrac{\ln\left(T_{\mathrm{feed}}/T_{\mathrm{ret}}\right)}{T_{\mathrm{feed}} - T_{\mathrm{ret}}}\right)}{\dot{W}_{\mathrm{E,net}}/\eta_{\mathrm{E}} + \dot{Q}_{\mathrm{DH}}/\eta_{\mathrm{Q}}}$$

where the fuel consumption for separate production is estimated on the basis of a 40% efficient (η_{E} = 40%) fuel-oil-fueled large-scale electricity-production power plant and either an 80% efficient (η_{Q} = 80%) methane-fueled thermal-energy-production single-family simple boiler or a 95% efficient (η_{Q} = 95%) methane-fueled thermal-energy-production large-scale simple boiler. It is noteworthy that $\eta''_{\mathrm{sep.prod.}} < \eta''$ for all cogeneration configurations, whereas of course for the electricity-only configurations the converse is true due to the fact that electricity-only net efficiency in the Brescia waste-to-energy facility never exceeds 29.4%.

With respect to the separate production of the same electric power $\dot{W}_{\mathrm{E,net}}$ and the same thermal power $\dot{Q}_{\mathrm{DH}}$ produced by the waste-to-energy facility, the rate of primary fuel savings is

$$\dot{m}_{\text{fuel savings}} = \frac{\dot{W}_{\mathrm{E,net}}/\eta_{\mathrm{E}} + \dot{Q}_{\mathrm{DH}}/\eta_{\mathrm{Q}}}{10{,}000\ \mathrm{kcal/kg}} \tag{1}$$

where of course 10,000 kcal/kg is the LHV of standard oil. The savings are computed in Table 1 in tep/h.

Table 1 and Figure 2 also report specific fuel savings in tep/t_{MSW2200}, i.e., per ton of municipal solid waste with LHV of 2200 kcal/kg, according to the relation

$$\frac{\dot{m}_{\text{fuel savings}}}{\dot{m}_{\mathrm{MSW2200}}} = \frac{\dot{W}_{\mathrm{E,net}}/\eta_{\mathrm{E}} + \dot{Q}_{\mathrm{DH}}/\eta_{\mathrm{Q}}}{\dot{m}_{\mathrm{MSW}}\ 10{,}000\ \mathrm{kcal/kg}}\ \frac{2200\ \mathrm{kcal/kg}}{\mathrm{LHV_{MSW}}} \tag{2}$$

The WTE facility is part of an existing district heating system powered by a main cogeneration facility consisting of three multifuel burners (two burning methane and fuel oil, one burning methane, fuel oil and coal) which produce superheated steam (510°C, 100 bar) for three independent backpressure turbines with vapor condensation in the district heating exchanger.

Therefore, in addition to the comparison with separate production, it is important to evaluate fuel savings with respect to cogeneration in the main Brescia facility of the same electric power $\dot{W}_{\mathrm{E,net}}$ and the same thermal power $\dot{Q}_{\mathrm{DH}}$ produced by the WTE facility. From an analysis based on the overall 1997 and 1998 performance data of the main cogeneration facility, assuming fuel allocation to electric and thermal energy production based respectively on the ratios

$$\frac{\frac{\mathrm{GWh_E}}{0.40}}{\frac{\mathrm{GWh_E}}{0.40} + \frac{\mathrm{GWh_Q}}{0.80}} \quad \text{and} \quad \frac{\frac{\mathrm{GWh_Q}}{0.80}}{\frac{\mathrm{GWh_E}}{0.40} + \frac{\mathrm{GWh_Q}}{0.80}}$$

we find that fuel savings with respect to the main Brescia cogeneration facility can be expressed again by Equations 1 and 2 with $\eta_{\mathrm{E}} = 0.588$ and $\eta_{\mathrm{Q}} = 1.176$.

4 Reduction of greenhouse gases with respect to landfilling

It is well known that landfills are the largest sources of anthropogenic methane emissions in the

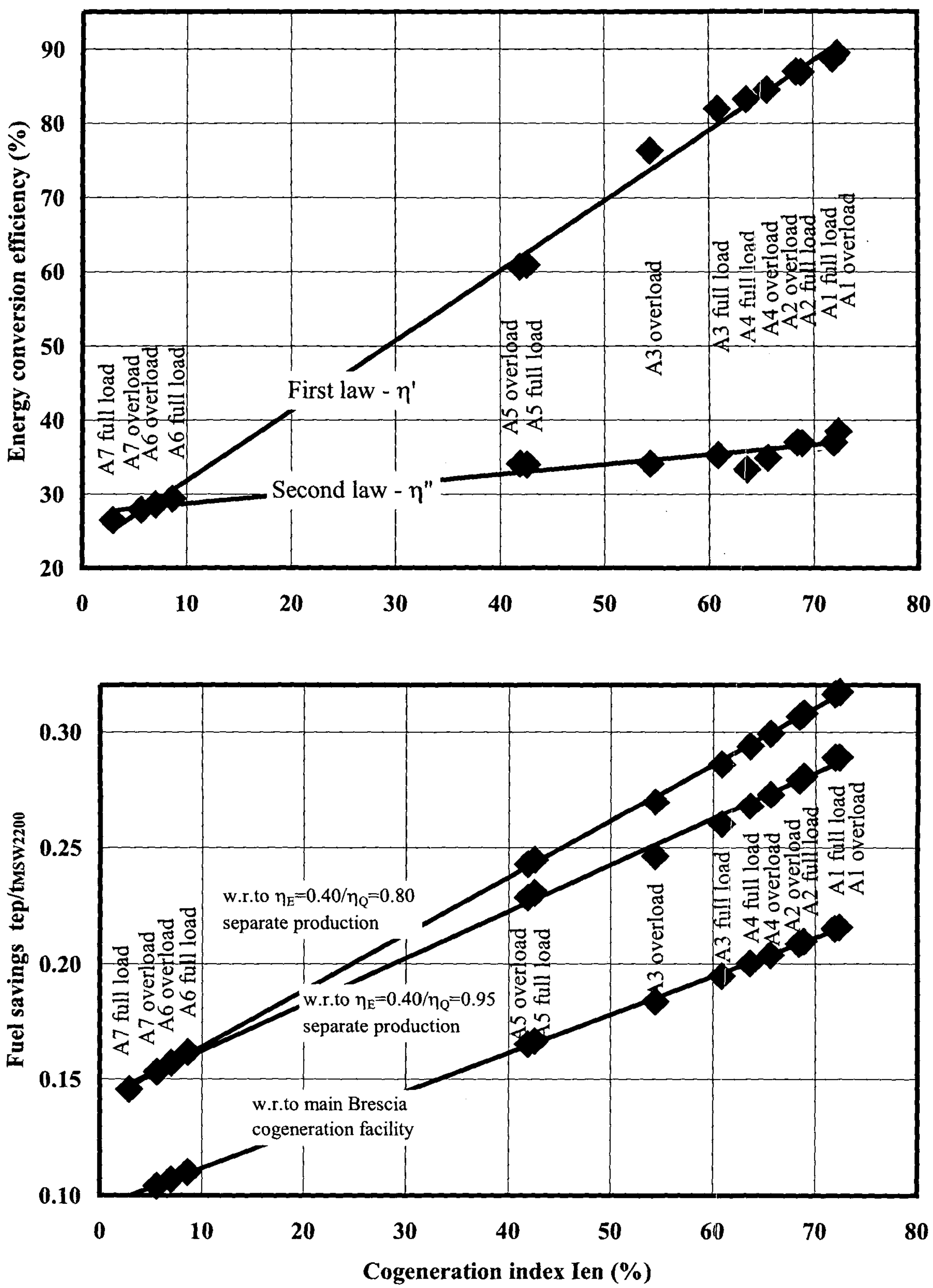

Fig. 2: First and second law efficiencies and fuel savings per ton of MSW with LHV of 2200 kcal/kg plotted as functions of the cogeneration index I_{en} for all configurations.

world and that on a 100 year climate-change scenario methane is a greenhouse gas about 21 times (on a weight basis) more "effective" than carbon dioxide.

Table 1 shows also the results of estimates of emissions of greenhouse gases resulting from trash processing in:

- the Brescia waste-to-energy facility;
- a high-level-technology controlled landfill with gas-to-energy conversion;
- a medium-level-technology controlled landfill with gas-to-energy conversion;
- a low-level-technology or uncontrolled landfill without gas-to-energy conversion.

Reduced emissions are expressed in terms of tons of CO_2 equivalent per ton of municipal solid waste (MSW) processed. We assume a factor of 21 kg of CO_2 equivalent per kg of CH_4 released in the atmosphere.[4] Table 2 summarizes the details of the estimate. Figure 3 shows the results as a function of the cogeneration index I_{en}. As is clear from Table 2, the CO_2 emissions avoided due to energy savings in the WTE facility depend on the type of means of electric and thermal energy production that it replaces. As detailed in Section 3, we evaluate fuel savings with respect to two levels of separate heat and electricity production as well as to cogeneration in the main Brescia facility. It is clear from Figure 3 and Table 1 that the differences are small as compared with the differences due to the wide range of levels of landfill gas-to-energy technology considered in the comparison.

The estimates are based on the following assumptions and refer to 1 ton of MSW with LHV of 2200 kcal/kg:

- carbon content of waste is 0.294 t_C/t_{MSW}; this value results from estimates of CO_2 stack emissions for each of the fourteen configurations, for which also the waste LHV has been estimated;
- CO_2 production due to aerobic and anaerobic processes in landfills is 0.431 t_{CO_2}/t_{MSW};
- CH_4 production in landfills is 0.157 t_{CH_4}/t_{MSW}. Of this amount, for top technology controlled gas-to-energy landfills:
  - 50% is collected and burnt in an energy recovery system, producing 0.216 t_{CO_2}/t_{MSW}; however the consequent fuel savings imply a CO_2 reduction of the same amount;
  - 40% is collected and burned in flares without energy recovery, producing 0.172 t_{CO_2}/t_{MSW};
  - 10% escapes into the atmosphere, contributing to the greenhouse effect like 0.329 t_{CO_2}/t_{MSW};

  for medium technology controlled gas-to-energy landfills:

  - 50% is collected and burnt in an energy recovery system, producing 0.216 t_{CO_2}/t_{MSW};
  - 30% is collected and burned in flares without energy recovery, producing 0.129 t_{CO_2}/t_{MSW};
  - 20% escapes into the atmosphere, contributing to the greenhouse-effect like 0.659 t_{CO_2}/t_{MSW};

  for low-level-techonology or uncontrolled landfills (in Italy this practice is now illegal, but most older landfills are of this kind):

  - 15% is collected and burned in flares without energy recovery, producing 0.065 t_{CO_2}/t_{MSW};
  - 85% escapes into the atmosphere, contributing to the greenhouse-effect like 2.799 t_{CO_2}/t_{MSW};
- because 80% of the carbon molecules contained in waste is of organic origin, we may assume that 0.862 t_{CO_2}/t_{RSU} will be reabsorbed by photosynthesis to recompose organic matter (in this sense MSW is an 80%−renewable energy source);
- in the Brescia WTE facility, incineration of waste produces 1.078 t_{CO_2}/t_{MSW};
- in addition, methane combustion used during start-up and maintenance operations produces 0.022 t_{CO_2}/t_{MSW};
- indicating with the variables

$$E = \frac{\dot{W}_{\mathrm{E,net}}}{\dot{m}_{\mathrm{W}}} \frac{2200\ \mathrm{kcal/kg}}{\mathrm{LHV}}$$

$$Q = \frac{\dot{Q}_{\mathrm{DH}}}{\dot{m}_{\mathrm{W}}} \frac{2200\ \mathrm{kcal/kg}}{\mathrm{LHV}}$$

the amounts of electric and thermal energy recovered by waste incineration in the WTE facility (expressed in $\mathrm{MWh}/t_{\mathrm{MSW2200}}$), the corresponding amount of CO_2 emissions avoided are given in Table 2 as functions of E and Q with respect to separate production of electricity with $\eta_E = 40\%$ and heat with either $\eta_Q = 80\%$ or $\eta_Q = 95\%$ as well as with respect to cogeneration of electricity and heat

Table 2: Comparison between production of greenhouse gases in the waste-to-energy facility versus production in landfills with various degrees of control and gas-to-energy technology.

Production of greenhouse gases, $t_{CO_2\ equiv.}/t_{MSW\ 2200}$			
Landfill			
	level of gas-to-energy technology		
	high	medium	low
CO_2 from aerobic and anaerobic processes	0.431	0.431	0.431
CO_2 from gas-to.energy combustion of CH_4	0.216	0.216	0
CO_2 from flared CH_4	0.172	0.129	0.065
CO_2 equiv. of CH_4 emitted to atmosphere	0.329	0.659	2.799
CO_2 avoided due to CH_4 energy savings	−0.216	−0.216	0
CO_2 reabsorbed by photosynthesis	−0.862		
Landfill total non renewable CO_2	0.071	0.357	2.433
Waste-to-energy facility			
	energy savings with respect to		
	separate production		main Brescia cogeneration facility
	$\eta_E = 0.40$ $\eta_Q = 0.80$	$\eta_E = 0.40$ $\eta_Q = 0.95$	
CO_2 avoided due to electric energy savings	$-0.714\,E$	$-0.714\,E$	$-0.649\,E$
CO_2 avoided due to thermal energy savings	$-0.257\,Q$	$-0.217\,Q$	$-0.234\,Q$
CO_2 from waste and CH_4 combustion	1.100		
CO_2 reabsorbed by photosynthesis	−0.862		
Waste-to-energy total non renewable CO_2	0.237 $-0.714\,E$ $-0.257\,Q$	0.237 $-0.714\,E$ $-0.217\,Q$	0.237 $-0.649\,E$ $-0.234\,Q$
Difference Waste-to-energy facility − Landfill			
	level of gas-to-energy technology		
	high	medium	low
With respect to separate production with $\eta_E = 0.40$ and $\eta_Q = 0.80$	0.167 $-0.714\,E$ $-0.257\,Q$	−0.119 $-0.714\,E$ $-0.257\,Q$	−2.195 $-0.714\,E$ $-0.257\,Q$
With respect to separate production with $\eta_E = 0.40$ and $\eta_Q = 0.95$	0.167 $-0.714\,E$ $-0.217\,Q$	−0.119 $-0.714\,E$ $-0.217\,Q$	−2.195 $-0.714\,E$ $-0.217\,Q$
With respect to cogeneration in the main Brescia facility	0.167 $-0.649\,E$ $-0.234\,Q$	−0.119 $-0.649\,E$ $-0.234\,Q$	−2.195 $-0.649\,E$ $-0.234\,Q$

Table 3: Estimates of the greenhouse gas reduction contributed by the waste-to-energy facility with respect to landfilling the same amount of waste incinerated during 1999 and producing the same amounts of electricity and heat produced during 1999.

Estimates of overall 1999 CO_2 reduction by means of the WTE facility			
$ton_{CO_2\ equiv.}/372{,}000\ ton_{MSW}$	With respect to landfills with high level of gas-to-energy technology	medium	low
With respect to separate production with $\eta_E = 0.40$ $\eta_Q = 0.80$	195,000	301,000	1,073,000
With respect to separate production with $\eta_E = 0.40$ $\eta_Q = 0.95$	186,000	292,000	1,064,000
With respect to cogeneration in the main Brescia facility	171,000	278,000	1,050,000

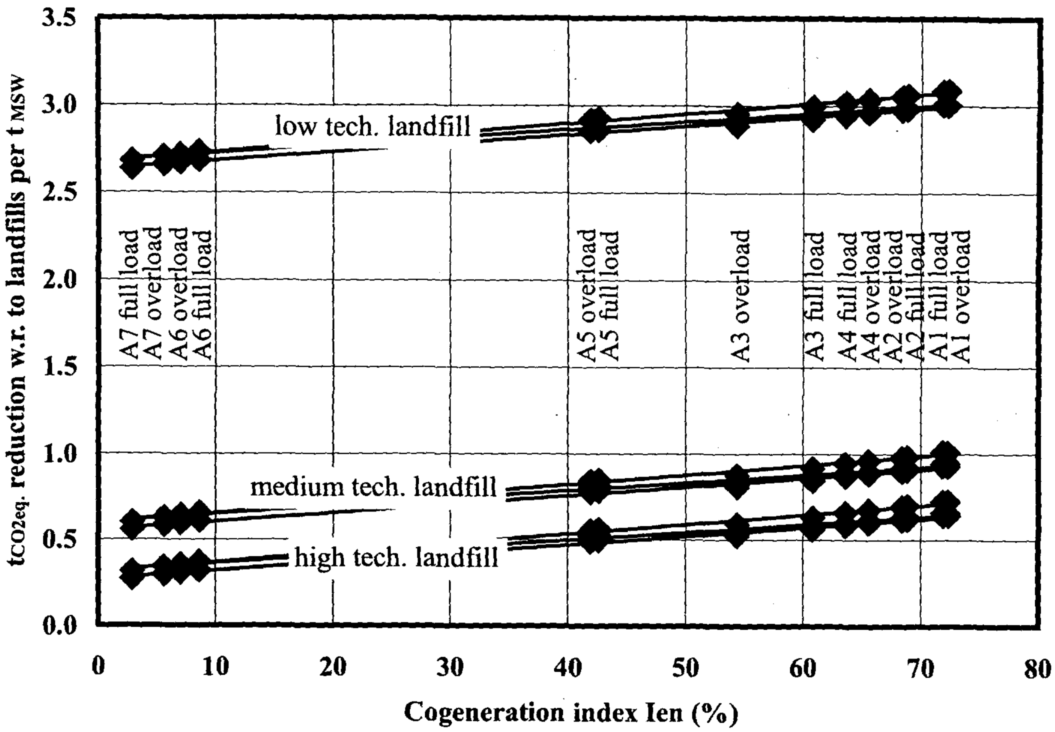

Fig. 3: Estimates of reduced emissions of greenhouse gases by means of the Brescia waste-to-energy facility as compared with landfills of various levels of gas-to-energy technology as functions of the cogeneration index I_{en}. The reductions due to energy savings are evaluated with respect to two levels of separate heat and electricity production and to cogeneration in the main Brescia facility, however the differences are small compared to those due to the different levels of landfill gas recovery.

in the main Brescia facility, assuming CO_2 allocation to electric and thermal energy production based respectively on the ratios

$$\frac{\frac{0.286}{0.40}}{\frac{0.286}{0.40}+\frac{0.206}{0.80}} \quad \text{and} \quad \frac{\frac{0.206}{0.80}}{\frac{0.286}{0.40}+\frac{0.206}{0.80}}$$

where 0.286 kg_{CO_2}/kWh_{FO} and 0.206 kg_{CO_2}/kWh_{CH_4} are the amounts of CO_2 produced per unit of thermal energy obtained by burning fuel oil and methane, respectively.

5 Conclusions

We presented and discussed performance data obtained as part of the acceptance tests of a new large-scale state-of-the-art-techonlogy waste-to-energy facility recently placed in service in Brescia, Italy, which is part of the oldest, largest and most advanced district heating system in Italy.

The facility is characterized by high emission standards and high energy efficiencies in all cogeneration and electricity-only configurations. The high degree of flexibility allows optimal integration with the main cogeneration facility that powers the Brescia district heating and utility system.

Estimates of the contribution of this facility to the reduction of greenhouse gases with respect to waste landfills, show that even when compared with state-of-the-art-technology gas-to-energy landfills and the main cogeneration facility, the reduction ranges from 0.27 to 0.64 ton of CO_2 (equivalent) per ton of waste depending on configuration (0.46 is the average value during 1999). The reduction is much higher and ranges from 2.64 to 3.01 ton of CO_2 (equivalent) per ton of waste (2.82 is the average value during 1999) if compared with low techonology landfills with no gas-to-energy conversion.

During 1999 the WTE facility processed 372,000 tons of waste with average LHV of about 2200 kcal/kg producing 278 GWh of net electric energy and 226 GWh of net thermal energy fed to the district heating system. Fuel savings with respect to separate production of electricity with $\eta_E = 40\%$ and heat with $\eta_Q = 80\%$ amount to 84,000 tep (80,000 if $\eta_Q = 95\%$). Fuel savings with respect to the main Brescia cogeneration facility amounts to 57,000 tep. Estimates of the yearly greenhouse gas reduction with respect to landfilling the same amount of waste and producing the same amounts of electricity and heat are shown in Table 3. These amounts show that the contribution of this single WTE facility to CO_2 reduction is significant: it ranges from 1% to 5% of the overall 2012 Italian goal with respect to the Kyoto protocol (from 4% to 20% of the 2002 goal).

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