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> ENERGY AND ENVIRONMENTAL BALANCES OF ENERGY RECOVERY FROM MUNICIPAL SOLID WASTE WITH AND WITHOUT RDF PRODUCTION

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Obiettivo Realizzativo 2.1
BILANCI ENERGETICI E AMBIENTALI DEL RECUPERO DI ENERGIA DAI RIFIUTI

Risultato R2.1 / 2
ANALISI COMPARATIVA DI TRE STRATEGIE PER RECUPERO DI ENERGIA DA RSU

A cura di:
Prof. S. Consonni, Prof. M. Giugliano, Prof. M. Grosso, Prof. L. Rigamonti

ENERGY AND ENVIRONMENTAL BALANCES OF ENERGY RECOVERY FROM MUNICIPAL SOLID WASTE WITH AND WITHOUT RDF PRODUCTION

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SUMMARY: The assessment of different options for energy recovery from waste proceeds from the unsorted, “Residual” Waste left downstream of Material Recovery and follows its fate along a number of alternative routes according to an LCA approach. The overall energy balance is based on the performance estimate of the waste-to-energy plant and of the co-combustion unit by means of a dedicated design and simulation tool developed at Politecnico di Milano. Results have been validated with actual data registered at state-of-the-art plants currently operating in Italy. Energy consumptions of the RDF production plant and of the handling of all the materials (waste, RDF, solid residues) were also included in the energy assessment. The overall environmental balance takes into account all the fluxes of pollutants released in the environment by each process, including both direct (those released from the waste treatment plants and from the transport of the materials) and indirect emissions (those related to the production of the reactants and to the construction of the plants). The positive emissions are compared with the avoided emissions, which are those released from fossil fuel-fired power production plants and boilers which produce the same amount of energy in the case of dedicated incinerators, or those released from the amount of fossil fuel displaced by the waste in the case of co-combustion. Results are discussed in terms of specific energy production, of emission inventories and of the principal impact indicators. For dedicated plants, energy recovery (electric and thermal) plays a basic role in the environmental balance; if this is combined with the very stringent air emission limits currently in force for WTE plants, a positive net result is obtained (i.e. most of the emissions from the WTE plant are lower than those from the power plants producing the same amount of energy). Co-combustion of RDF in industrial plants shows interesting results, too, especially in terms of reduction of greenhouse gas emissions; concerns related to the possible long-term effects of the operation in co-combustion mode call for careful monitoring of the operational history. Dedicated WTE plants fed directly with Residual Waste appear most suited to large scale waste management systems with a highly concentrated waste production, even more if the WTE plant cogenerates heat and power. The production of RDF and its co-combustion in industrial plants might be preferable for small scale waste management systems where a facility that can be adapted to co-combustion is available. The potential of co-

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combustion on the national scale is finally assessed by referring to the sites and the capacity for cement production now installed in Italy, as well as to the coal-fired electric capacity envisagedfor the near future.

1. INTRODUCTION

Since 2000, Federambiente (the federation of Italian municipal companies managing environmental services) has sponsored research at Politecnico di Milano to assess benefits and caveats of alternative strategies for energy recovery (Fig. 1.1) from Residual Waste (RW) collected after Material Recovery (MR). A first study on the comparison between the utilisation of RW and RDF in "dedicated" Waste-To-Energy (WTE) plants was completed in 2002 (Consonni et al., 2005a-b). The major outcomes of this study were the followings:

- producing RDF to subsequently use it in dedicated plants appears to offer no advantage over the "direct" use of RW in grate combustor WTE plants;
- compared to "direct" energy recovery from RW, strategies based on RDF reduce energy savings by 10-40%, reduce environmental indicators by up to 90% and increase costs by up to 80%;
- the more sophisticated and complex is the process adopted to produce RDF, the higher are the losses;
- economies of scale give a very strong advantage to large Waste Management Systems (WMS) compared to smaller ones;
- for dedicated plants, best option is large cogenerative WTE plant with "direct" feed of RW.

Starting from these considerations, the present paper illustrates the results of the study on "non-dedicated" plants carried out in 2004-05. The study focuses on the co-combustion of RDF in large-scale power stations and cement kilns**.**

It must be pointed out that the results on RDF co-combustion scenarios are based on relatively limited sets of experimental data. As such, they must be regarded as preliminary. A further data acquisition is currently being discussed with Federambiente and plant operators.

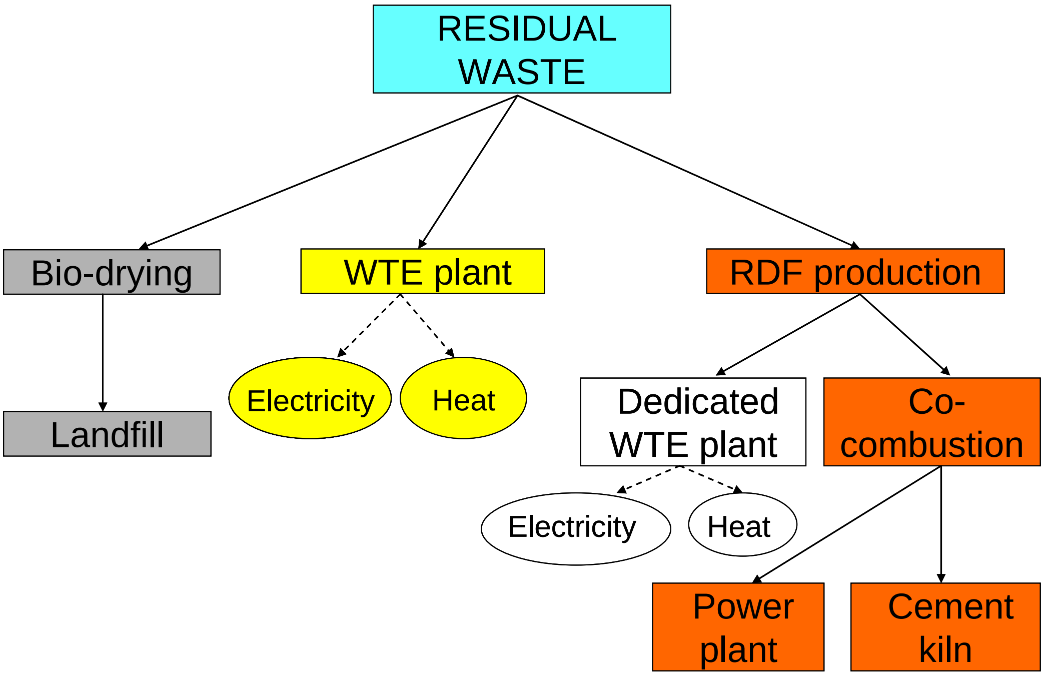


Figure 1.1. Systems of interest for the overall assessment of waste-to-energy pathways

2. MATERIALS AND METHODS

2.1 Strategies, reference systems and scenarios

Four strategies have been considered, which are illustrated in Fig. 2.1. Strategy “0” (landfill disposal of the whole RW after bio-drying) was included as a reference strategy, as it should not be considered in a WMS which complies with the EU Directives on waste management. The bio-drying pre-treatment was introduced in order to meet the requirements of Directive 1999/31/EU concerning the targets of reduction of degradable waste disposal in landfills.

Strategy 1 is based on the direct incineration of RW in a grate combustor without any pre-treatment, while in strategies 2 and 3 the RW is processed into RDF for co-combustion in a power plant and a cement kiln, respectively.

To illustrate the relevance of scale, the comparison among the different strategies was carried out for two system sizes:

- a “small” Waste Management System (WMS) with a gross MSW production of 100,000 t/yr (65,000 t/yr after MR);
- a “large” WMS with a gross MSW production of 600,000 t/yr (390,000 t/yr after MR).

Given the specific gross generation of MSW in Italy and most European Union countries – approximately 500 kg per person per year – the small WMS is representative of a small province or a medium-size city with 200,000 inhabitants, whereas the large WMS is representative of a large city with 1,200,000 inhabitants.

Finally three different scenarios for the evaluation of avoided energy consumption and emissions were considered:

- Scenario 1: Electricity generated from WTE plant (or landfill gas) substitutes electricity generated by a Steam Cycle (SC) fed with 50% natural gas and 50% oil. Heat generated from WTE plant substitutes heat generated by household boilers fed with fuel oil;
- Scenario 2: Electricity generated from WTE plant (or landfill gas) substitutes electricity generated by a Combined Cycle fed with natural gas. Heat generated from WTE plant substitutes heat generated by household boilers fed with natural gas;
- Scenario 3: Electricity generated from WTE plant (or landfill gas) substitutes electricity generated by a Steam Cycle (SC) fed with coal. Heat generated from WTE plant substitutes heat generated by household boilers fed with fuel oil.

The three scenarios apply to the assessment of Strategies 0 and 1 only, because when co-combustion is considered (strategies 2 and 3) the avoided energy consumption and emissions are those deriving from the amount of fossil fuel which is directly displaced by the RDF.

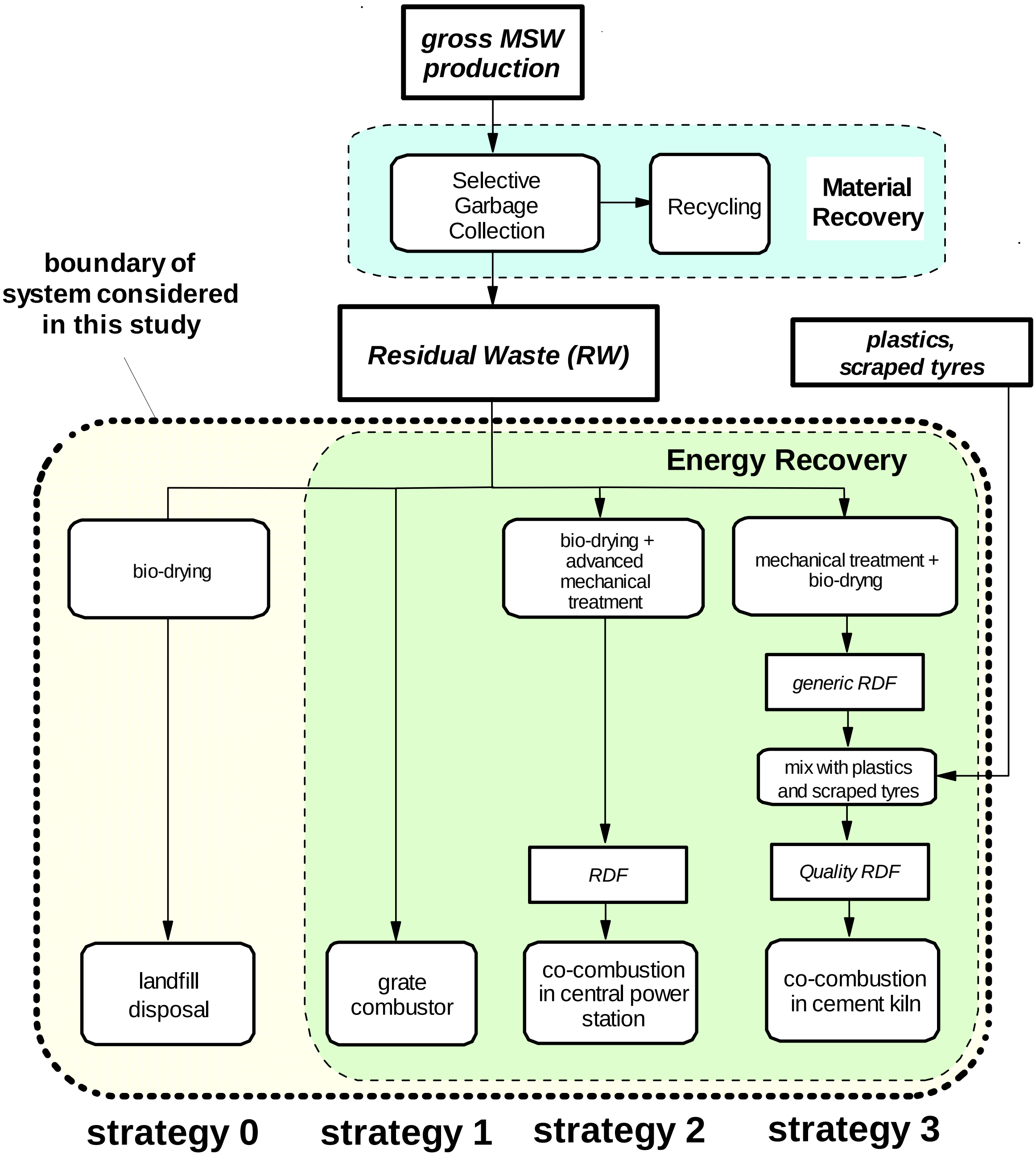


Figure 2.1. Strategies considered in this study

2.2 System configuration

Figs. 2.2-2.5 show the basic mass fluxes and energy balances of the four strategies, including some further data that have been utilised for the LCA (Life Cycle Assessment) comparison. The figures clearly illustrate also the boundaries of the systems.

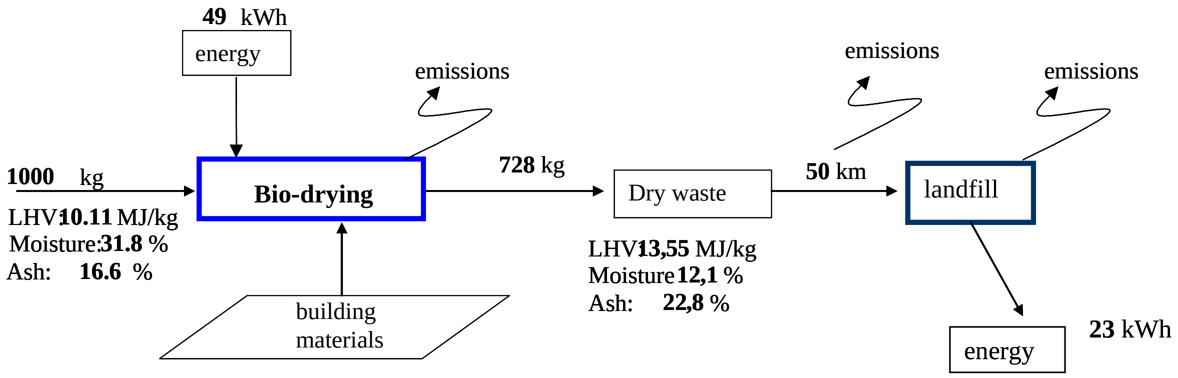


Figure 2.2. Strategy 0: bio-drying + landfill

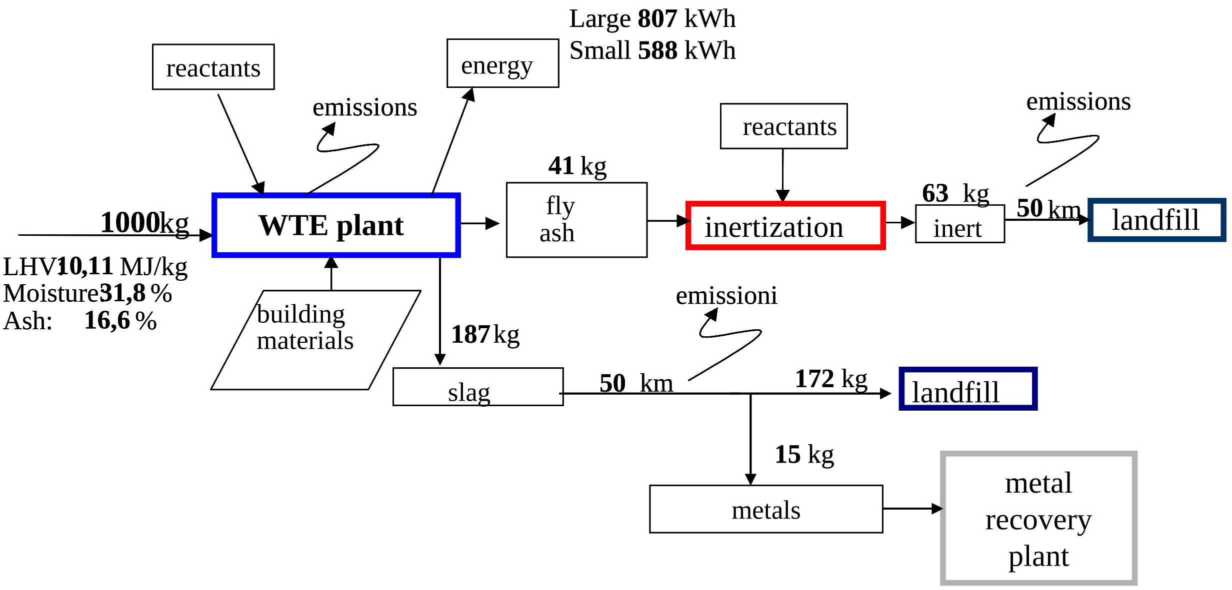


Figure 2.3. Strategy 1: Residual Waste fed directly to a dedicated WTE plant with grate combustor

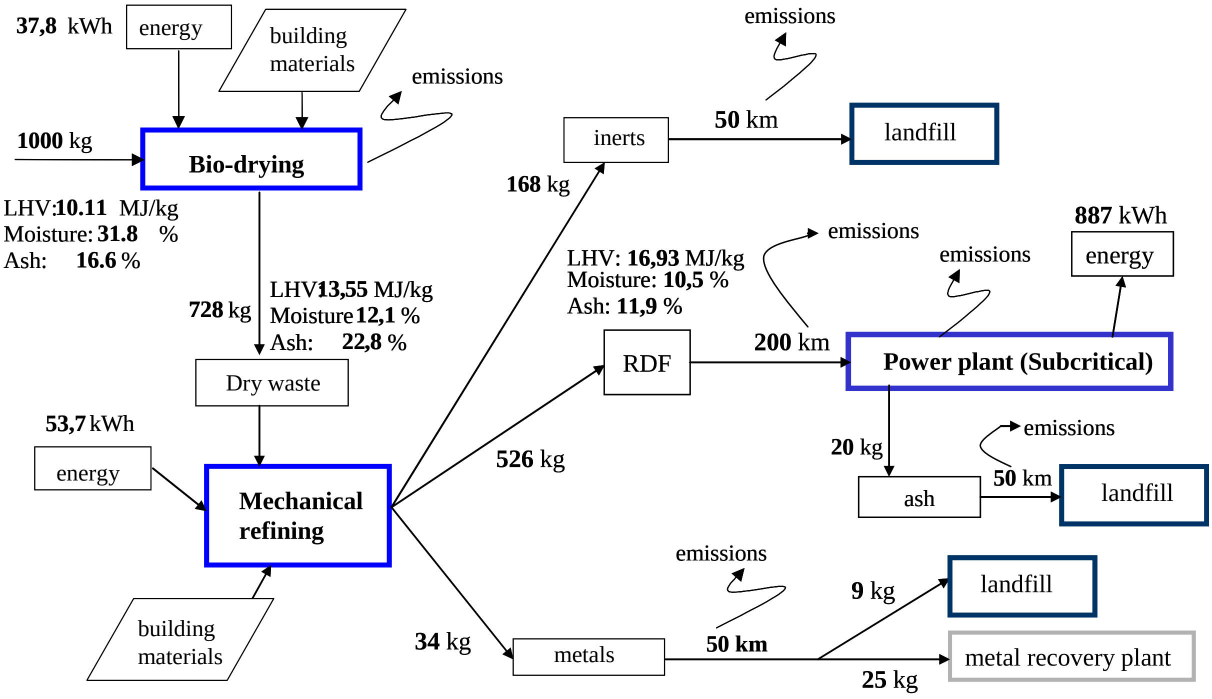


Figure 2.4. Strategy 2: RDF production and its co-combustion in a fossil-fuel-fired power station

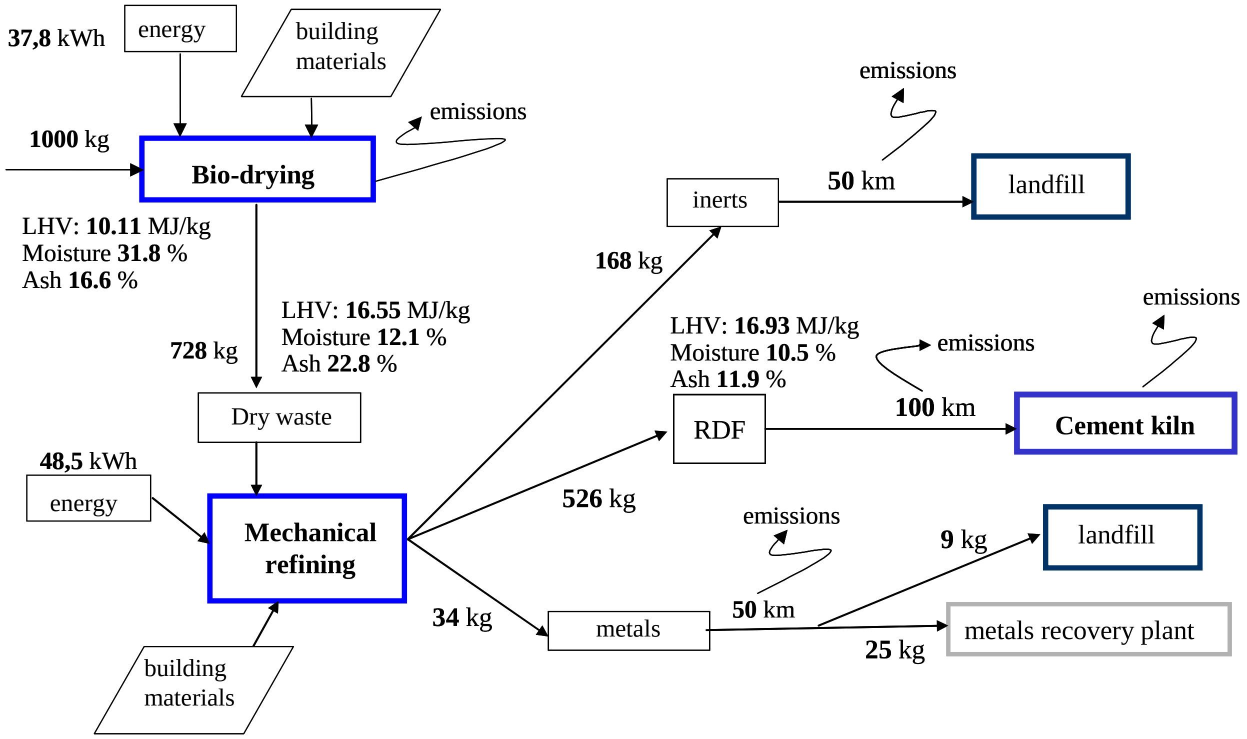


Figure 2.5. Strategy 3: RDF production and its co-combustion in a cement kiln

2.3 Residual waste and RDF characteristics

For all the considered strategies, the functional unit is represented by 1 t of unsorted residual waste collected downstream selective collection for material recovery. Based on the typical composition registered in large metropolitan areas of northern Italy, we have assumed the figures reported in Tab. 2.1.

Table 2.1. Hypothesised composition of Residual Waste (RW) downstream selective collection

constituent	content in RW	composition: moisture	composition: ash	composition: volatile fraction	carbon content: total	carbon content: % renewable	LHV
	% by weight	% by weight	% by weight	% by weight	% by weight	% by weight	MJ/kg
paper & cardboard	24.5	14.0	5.0	81.0	37.6	100	13.22
wood	6.0	22.0	1.5	76.5	37.6	100	13.87
plastic	19.0	6.0	9.0	85.0	55.5	0	26.18
glass & inert material	3.5	2.5	95.0	2.5	1.0	0	-0.061
metals	3.5	5.0	92.5	2.5	1.0	0	-0.122
organic fraction	31.5	70.0	9.0	21.0	9.6	100	1.719
fines	12.0	30.0	35.0	35.0	20.5	60	4.395
Residual Waste	**100**	**31.8**	**16.6**	**51.6**	**27.6**	**16.0**	**10.11**

volatile fraction % by weight of total	
C	27.6
Cl	0.64
H	3.49
O	19.7
N	0.15
S	0.06
Total	**51.6**

In strategies 2 and 3 RDF is produced, starting from RW, by means of a conventional Mechanical-Biological Treatment plant (MBT), based on a bio-drying process followed by mechanical refining. Fig. 2.6 reports the mass and energy balance of the overall RDF production process. The yield of RDF production is 52.6%, while its energy content corresponds to 88% of the energy content of the residual waste.

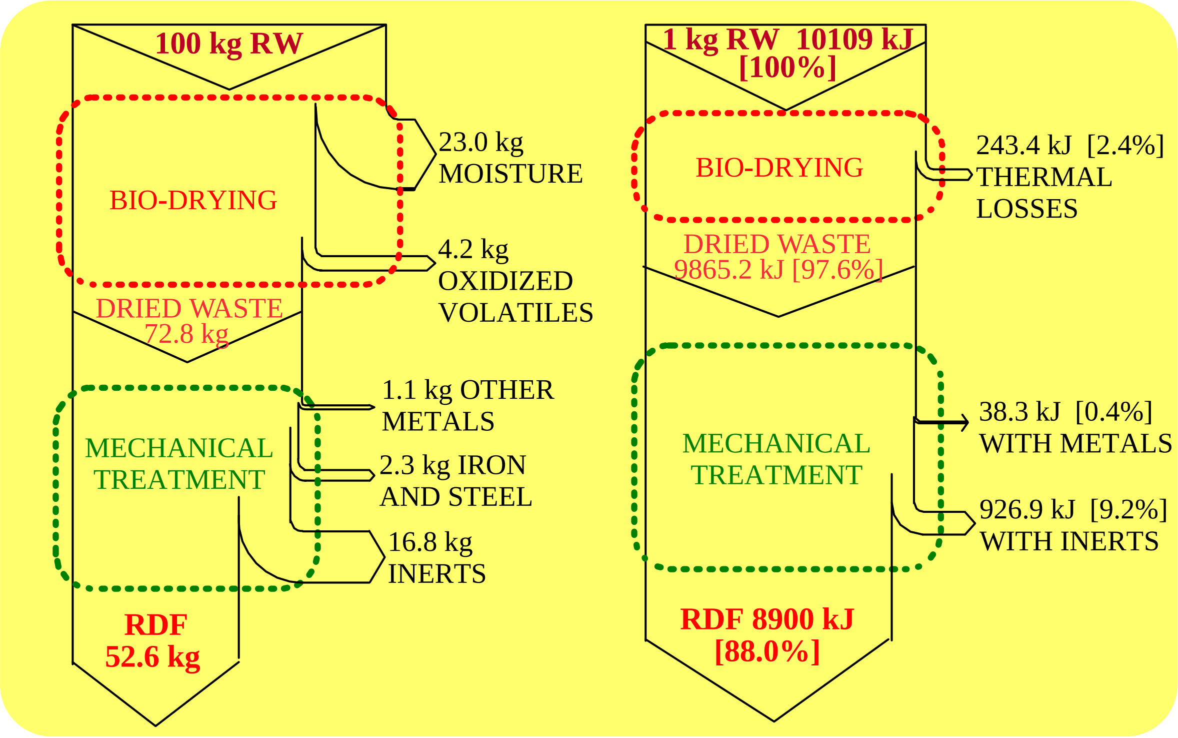


Figure 2.6. Mass and energy balances of RDF production

2.4 Simulation of energy conversion processes

The code used to estimate the performances of WTE plants was originally developed to simulate natural gas combined cycles (Consonni, 1992) and then extended to handle essentially all types of power plants based on gas and/or steam cycles (Chiesa et al, 1993; Macchi et al., 1995; Consonni, 2000b), including those fired with unconventional fuels like biomass, heavy residues, waste, etc. The system of interest is defined as an ensemble of components, each belonging to one of sixteen basic types: pump, compressor, turbine, heat exchanger, combustor, gas turbine expander, chemical reactor, etc. Basic characteristics and mass/energy balances of each component are calculated sequentially and iteratively until the conditions at all interconnections converge to stable values.

The model accounts for all major phenomena and mechanisms affecting the performances of WTE systems: combustion; heat transfer; heat losses; losses due to unburnt fractions; pressure drops, variation of turbomachinery efficiency with scale and stage similarity parameters; auxiliary power consumption, etc. Thermodynamic properties are calculated according to the JANAF tables (Stull and Prophet, 1971; Gardiner, 1984) except for water and steam, which conform to SI tables (Schmidt, 1982).

2.5 Environmental assessment

Environmental assessment was carried out with the LCA technique, taking into consideration all direct and indirect atmospheric emissions.

The Emission Inventory identifies and quantifies the whole set of emissions into the environment resulting from the processes being considered. In this work the following atmospheric emissions have been considered:

- emissions at the stack of WTE plants;
- emissions from the bio-drying of the RW;
- emissions from the transport of solid residues to landfill;
- residual emissions from landfill (only for Strategy 0);
- emissions related to the production of reactants and additives for flue gas treatment and residues inertisation: sodium bicarbonate, activated carbon, ammonia, cement, bentonite and sodium silicate;
- emissions related to the production of building materials: steel and concrete for WTE plant and waste handling facilities;
- avoided emissions from power stations and thermal plants displaced by the WTE plant, according to the three scenarios previously described;
- avoided emissions from the production of steel and aluminium from the metal scrap recovered from the inert materials and from the bottom ash.

For co-combustion in strategies 2 and 3, data derives from the measured stack concentrations during “blank” operation (without RDF co-combustion) and during RDF co-combustion, and were supplied by ARPAV for Strategy 2 (ARPAV, 2003) and by the cement kiln operator for strategy 3. RDF thermal substitution rate was 5% for both the power plant and the cement kiln.

LCA was based on the CML Guidelines (CML, 2001). The SimaPro6® commercial software (PRè Consultants, 2004) was utilised for the final calculations of the emission inventory and of the four major impact indicators:

- Global Warming Potential (GWP – kgCO_2 eq.)
- Human Toxicity Potential (HTTP – kg 1,4-DCB eq.)
- Acidification Potential (AP – kgSO_2 eq.)
- Photochemical Ozone Creation Potential (POCP – kgC_2H_4 eq.)

A detailed description of the LCA technique falls beyond the scope of this paper, but it can be found in Consonni et al. (2005b).

3. RESULTS AND DISCUSSION

3.1 Energy balance

Fig. 3.1 illustrates the overall efficiency of electricity production for Strategies 1 and 2. This result obviously does not apply to Strategy 3, where the final product of the RDF co-combustion is cement and not electric energy. For dedicated WTE plant of Strategy 1, the electric-only operation mode has been included in this comparison, while for Strategy 2 two different types of coal-fired power plant were considered:

- a conventional sub-critical steam cycle (Strategy 2 SUB) like the one utilised during the experimental assessment;
- a more advanced ultra-super-critical steam cycle (Strategy 2 USC), that will be the basis of the new coal-fired plants that will be realised in Italy in the near future, but where there is a lack of RDF co-combustion evaluation.

The overall net efficiency of energy production has been calculated by subtracting to the total efficiency of the power plant the loss of LHV during RDF production (reported in Fig. 2.6) and the loss due to auxiliaries for RDF production (reported in Fig. 2.4 and 2.5).

By evaluating the results it appears that the overall efficiency of electricity production by the co-combustion of RDF into sub-critical power plants (28,33%) is about the same of the combustion of RW into a state-of-the-art, large WTE plant (28,77%). In fact the higher efficiency of the sub-critical power plant (35,88%) compared to the WTE plant is vanished by the losses related to the RDF production process. On the other side, when the small WMS is considered, the efficiency of co-combustion of RDF into sub-critical power plants may be assumed constant, and then it gives much more electricity than the small WTE plants fed with RW, whose efficiency is strongly affected by negative economies of scale, and falls down to 19.47%.

A significant advantage of the RDF co-combustion in power plants comes when the USC steam cycle is considered, with an overall net efficiency of 34,31%, clearly superior than the WTE plant fed with RW.

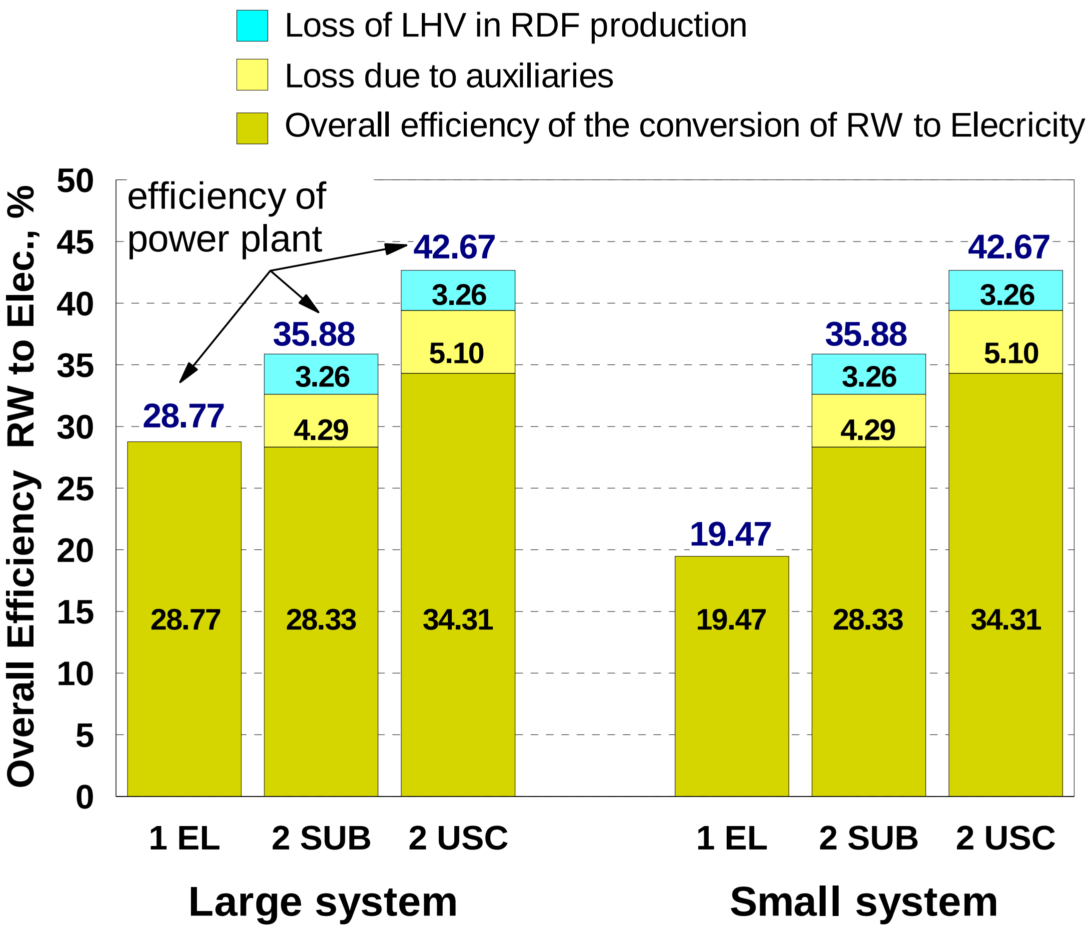


Figure 3.1. Overall efficiency of electric energy production for strategies 1 and 2 (electric energy production does not apply to strategy 3)

The evaluation of primary energy savings, expressed in terms of kg of oil equivalent and reported in Fig. 3.2, for Strategies 0 and 1 is strongly dependent on the hypothesised scenario for the avoided energy consumption. On the other hand, for co-combustion strategies this is more straightforward as the avoided primary energy equals the exact amount of coal or petcoke which is directly replaced by RDF. Then in Fig. 3.2 the results for Strategies 0 and 1 are reported in term of a range of values, while for 2 and 3 in terms of a single figure.

It can be clearly noted that the primary energy savings generated by the co-combustion of RDF and by the combustion of RW into WTE plants are similar, especially when large, cogenerative WTE are considered.

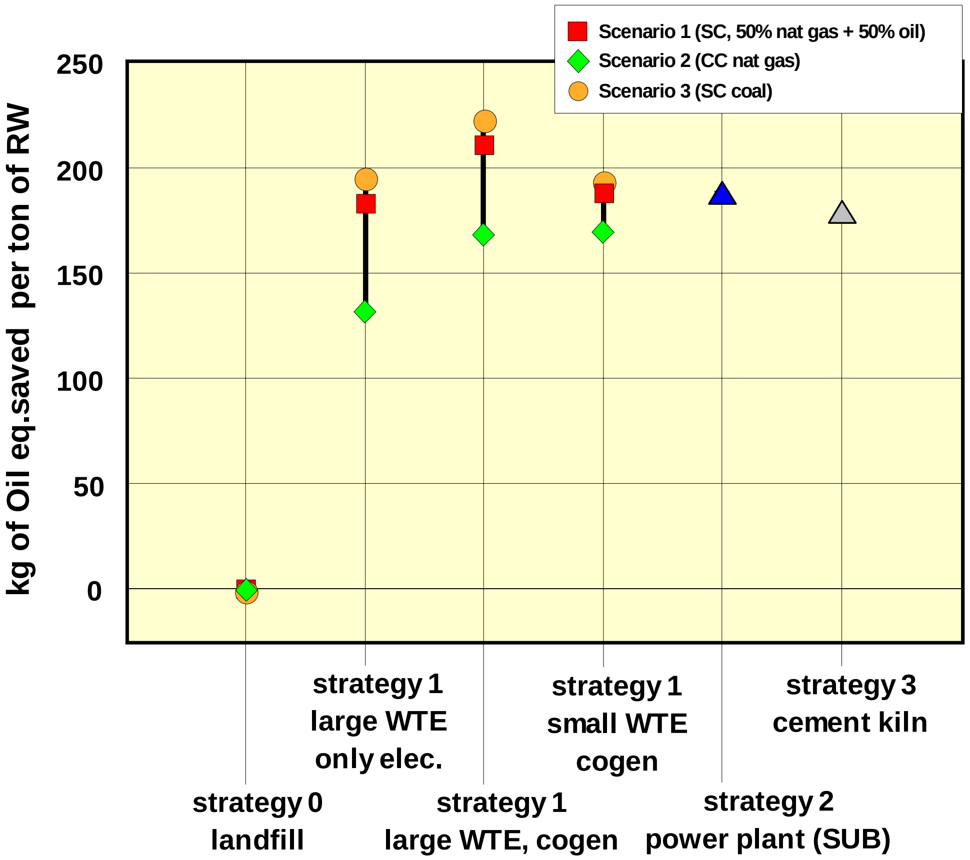


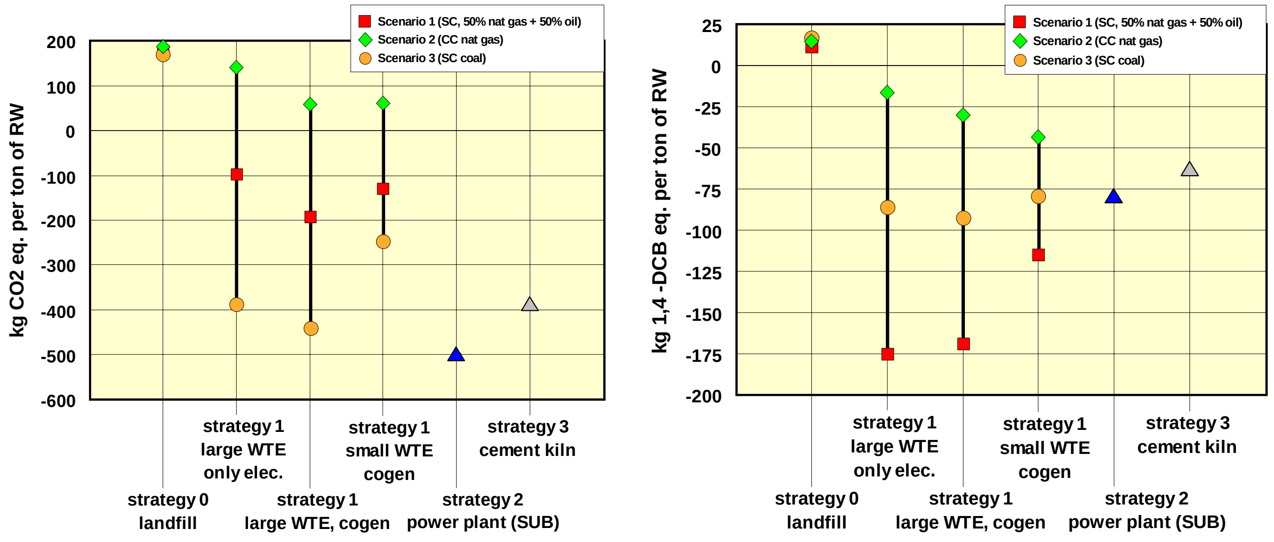
Figure 3.2. Primary energy savings expressed in term of kg of oil equivalent

3.2 Emissions and environmental indicators

Fig. 3.3 reports the four environmental impact indicators for the different strategies. Once again for Strategies 0 and 1 a range is shown, which is related to the three scenarios of avoided energy consumption and emissions.

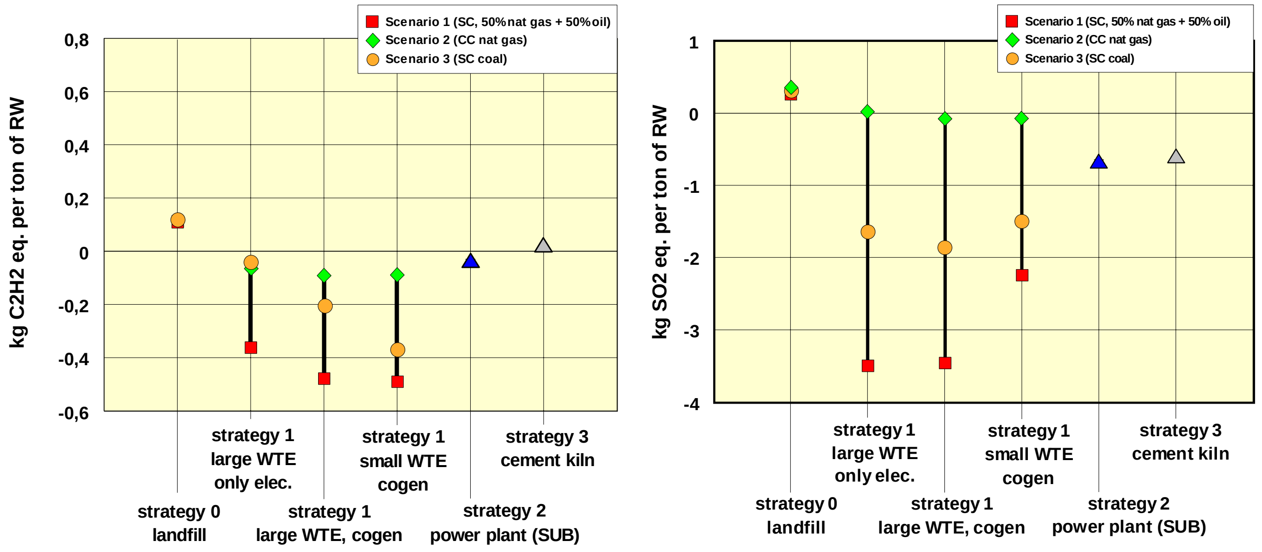
It is clear that co-combustion of RDF gives lower GWP than RW combustion into WTE plants, thanks to the direct replacement of coal. In fact Strategy 1 gives results similar to Strategies 2 and 3 only when the coal-based Scenario 3 is considered.

Strategy 1 gives lower Photochemical Ozone Creation (POCP) than the co-combustion strategies, while a more complex situation is obtained for Human Toxicity Potential (HTP) and Acidification Potential (AP). The reference Scenario becomes then crucial to assess the relative ranking of the different strategies.



GWP

HTP



POCP

AP

Figure 3.3. Environmental impact indicators for the three strategies

3.3 Potential in the Italian context

A preliminary evaluation of the potential for the different strategies of energy recovery in the Italian context is depicted in Table 3.1. The hypotheses which have been adopted are described in the footnotes of the table. While the recourse to dedicated WTE plants might be sufficient to fulfil the overall waste disposal requirement, the RDF co-combustion is obviously limited by the number and geographical location of existing industrial plants. A massive recourse to RDF co-combustion in both the existing cement kilns and the USC coal-fired power plants envisaged for the near future might contribute to 18 – 38% of the amount of RW.

Table 3.1. Preliminary assessment of the potential for energy recovery from waste in Italy

	Amount of RW or RDF treated with energy recovery	**Corresponding amount of Residual Waste (RW)**		**Inert residues to landfill**
	$t \cdot y^{-1}$	$t \cdot y^{-1}$	% of Italian production	$t \cdot y^{-1}$
Strategy 1, large	11,000,000 (1)	11.000.000	57	2.600.000
Strategy 1, small	7,500,000 (2)	7.500.000	39	1.800.000
Strategy 2 (power plant)	1,600,000 - 3,200,000 (3)	3,050,000 - 6,100,000	15 - 31	600,000 - 1,200,000
Strategy 3 (cement kiln)	350,000 - 700,000 (4)	670,000 - 1,330,000	3.3 - 6.7	120,000 - 240,000

(1) RW of the provinces with a gross MSW production larger than 300,000 $t\ y^{-1}$

(2) RW of the provinces with a gross MSW production between 100,000 and 300,000 $t\ y^{-1}$

(3) Assuming that all coal-fired subcritical plants run in co-combustion, with 5% to 10% of the heat input provided by RDF. This requires that all such subcritical plants will be equipped with adequate flue gas treatment: at least ElectroStatic Precipitator (ESP) + catalytic deNOx (SCR) + Flue Gas Desulfurization (FGD)

(4) Assuming that 60% of the cement kilns run in co-combustion, with 10% and 20% of the heat input provided by RDF.

3.4 Economic considerations

A detailed economic assessment falls beyond the scope of this paper; still some considerations can be made on the potential market value of RDF.

The overall RDF production cost has been estimated equal to 57 € per ton of Residual Waste, and it can be assumed roughly constant for both small and large WMS. On the other side, the overall cost of RW management in Strategy 1 in the hypothesis of a sale price of 80 €/MWh for electric energy and 30 €/MWh for thermal energy corresponds to:

- for large WMS:
    - 34 € per ton of RW (only electric mode)
    - 27 € per ton of RW (CHP mode)
- for small WMS:
    - 107 € per ton of RW (only electric mode)
    - 92 € per ton of RW (CHP mode)

It is then possible to estimate the market price of RDF that equals the overall cost of Strategy 1 for the different options considered. Taking into account the fact that for large WMS the overall cost for Strategy 1 is always lower than the RDF production cost and vice versa for small WMS, it is clear that the market price of RDF will be positive or negative, respectively.

In order to break even with the economic return of a small WTE plant, an RDF producer can then afford to pay for the “disposal” of RDF to a non-dedicated plant where it is co-combusted to generate energy; at the reported electricity price of 80 €/MWh, the RDF producer can afford to pay between 67 and 97 € per ton of RDF.

In order to break even with the economic return of a large WTE plant, an RDF producer needs to be paid to supply the RDF to a non-dedicated plant where it is co-combusted to generate energy; in particular the RDF producer needs to sell RDF at a price included between 44 and 57 € per ton of RDF.

4. CONCLUSIONS

Different strategies of energy recovery from residual waste, based on direct incineration in WTE plant and on RDF production and its subsequent co-combustion in industrial plants have been assessed based on mass, energy, environmental and economic considerations.

Based on the results of a previous evaluation (Consonni et al., 2005a-b), when the option of a dedicated WTE plant is chosen, it is not convenient to feed it with RDF rather than RW, because the environmental, energetic and economic burdens of RDF production cannot be compensated by a better energy recovery efficiency in the WTE plant. Then the most viable option is the one based on direct combustion of RW in a large-scale grate combustor.

The RDF production option gains interest when its energy content might be recovered with a significantly higher efficiency than what can be obtained in a traditional WTE plant, as is the case for co-combustion in suitable coal-fired power plants or cement kilns.

The results of the comparison between direct incineration of RW and co-combustion of RDF can then be summarised in the following points:

- the overall efficiency of electricity production by the co-combustion of RDF into sub-critical coal-fired power stations is about the same of the combustion of RW into a state-of-the-art, large-scale WTE plant;
- the co-combustion of RDF into sub-critical power stations gives however much more electricity than small WTE plants fed with RW;
- RDF + co-combustion into Ultra-supercritical Steam Cycles (USC) is superior to the use of RW into WTE plants, although less likely due to the sophistication of USC plants;
- primary energy savings generated by the co-combustion of RDF and by the combustion of RW into WTE plants are similar. Large, cogenerative WTE plants achieve the highest savings;
- co-combustion of RDF tends to give lower GWP than RW into WTE plants;
- RW into WTE plants gives lower Photochemical Ozone Creation;
- a more complex situation occurs for Human Toxicity Potential and Acidification Potential. In this case the reference Scenario of avoided emissions is crucial to assess the relative ranking;
- if all the suitable cement kilns and all the new coal-fired power plants will be utilised for co-combustion, the potential for RDF treatment in Italy is included between 18% (in case of conservative thermal substitution rate) and 38% (in case of a more optimistic thermal substitution rate) of the total RW;
- RDF production and its co-combustion are economically favourable compared to direct utilisation of RW in a dedicated plant only for small-scale WMS; vice-versa for large-scale ones, where the economies of scale of a large WTE plant allow for a treatment cost significantly lower than the cost for RDF production, thus requiring the RDF to be paid for by the final utilisator.

Unlike in the comparison between Residual Waste in WTE plants versus RDF in “dedicated” plants, where the former “wins” all across the board, in the comparison between Residual Waste in WTE plant and RDF co-combustion in “non-dedicated” plants no technology “wins” across all indicators. Large WTE plants fed with RW are most suited to serve large communities, even more when they feed a district heating system in cogeneration. RDF + co-combustion may be a viable opportunity for small communities where a suitable plant that can safely handle RDF is available. It is unlikely that co-combustion alone can be the solution to the treatment of all RW generated in an industrial country.

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