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Energy enhancement of solid recovered fuel within systems of conventional thermal power generation

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Abstract

The main objective of this article is to verify the feasibility, in terms of technical and economical issues, of a new refuse-derived fuel SRF (Solid Recovered Fuel) to be used as a new fuel in a thermal power station or in an incineration plants. By means of the innovative micronization technology it is possible to produce SRF suitable for the technical specifications of the plants which, taking into account appropriate modifications, could be reconverted and not decommissioned. The present energy supply scenario shows a partial contraction of the activities of power plant thermal generation despite an increase of the power demand and despite one of the highest energy cost in Europe. It is likely to surmise a gradual stall of such activities and finally the decommissioning due to the fact that plants will turn out to be not economically productive. On the other hand, it is now necessary to promote adequate policies for sustainable waste management. An opportunity in this sense is represented by the smart usage (made possible through innovative manufacturing processes) of the SRF as an energy source. The tests conducted on the innovative chemical-mechanical micronization technology showed an average energetic cost of 30 kWh/ton, and an average production cost of 15 €/ton for the 0.5 mm size. Combustion tests showed a good environmental and combustion performance. In this article, the refuse-derived fuel (which is governed according to the Decrees of the Ministry of Environment, Land and Sea) has been obtained through an innovative technology of chemical-mechanical micronization. We have also proceeded to verify the functional feasibility of the fuel production in order to feed incinerators and power plants in partial or total substitution of the conventional fuels (coal, fuel oil).

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Keywords: Solid Recovered Fuel; CSS; Municipal Solid Waste; Waste to energy; Energy Recovery; Co-combustion; Mechanical biological treatment; Micronization; Fuel characterisation; Alternative fuel;

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1. Introduction

Italy is one of the most industrialized countries depending on foreign imports of energy sources, with marked balance of payments imbalances. Strategic considerations related to accruing global fuel crisis require diversification of the energy mix, reduction of dependence on fossil fuels and greater security and stability of energy supply. It is necessary to promote the availability and use of alternative fuels, paying particular attention to *waste derived fuels* (WDFs) including *solid recovered fuels* (SRFs) having more stable physical-chemical properties than the constituent raw material and markedly cheaper than primary fuels and because of this willingly utilized in energy intensive industrial sectors such as cement industry, pulp and paper industry, thermal power plants [1]. Production and utilisation of the SRF increase level of waste recovery (improving the compliance to EU requirements related to waste management), allows energy recovery and finally transform the waste problem into a resource for productive sector and the community (e.g. waste tax reduction). In the EU research has been conducted for many years on reprocessing different groups of wastes into the alternative fuels, bringing about the implementation of series of technological solutions on the industrial scale. Both international corporations and local companies are engaged in technology development process of alternative fuels from wastes with the appearance of many technological solutions suited to the composition of the local raw material and to the requirements of the local consumer.

The aim of this study is to analyze more in depth the technical and economic feasibility of reconversion of thermal power plants in production downtime by replacing conventional fuel with high-quality SRFs up to 10% w/w of the regular fuels, which proved a solution easy to implement, with low investment costs and appropriate economic and environmental performance. The achievable benefits consist in enhancing plant management, keeping emissions at a substantially invariable level. Pilot projects in Europe have identified a new frontier in the co-combustion of coal with a new low-cost starting material obtained directly from municipal solid wastes (MSW) with scouting and subsequent testing of new technologies.

In 2010 the waste production in Italy is about 32 Mt/y of MSW and the waste management criticality, especially in regions such as Campania, Lazio, Sicily and Calabria, is set to worsen for the need to close part of the landfills where they are currently conferred more of 13 Mt/y. The amount authorized for the waste treatment exceed 6,5 Mt/y and the current production of SRF is about 2 Mt/y. In addition, special waste, similar and non-hazardous (the total amount, especially from industry, is about 160 Mt) not covered by provincial and regional programming is a important amount that must necessarily be treated and managed [2][3]. Is therefore essential to carry out, as well as to the reduction of waste upstream (prevention and eco-design) by starting the re-use, drastically reducing the quantities to landfill, increasing materials and energy recovery in the same way as is done in European countries the most virtuous. Indeed Austria, Germany, The Netherlands and Sweden, the best performing countries in Europe, have experienced high levels of recycling (50-60% material recovery) deeply integrated with high rates of energy recovery (40-50% energy recovery) in thermal power stations, confirming that the solution of the problem to be found with a set of actions, in which the energy recovery must play a decisive role [4].

Nomenclature

t	ton (1000 kg)	GCV	Calorific Value
t/y	ton per year	NCV	Net Calorific Value
t/h	tonnes per hour	d	in a dry state
w/w	Weight fraction or percentage	MBT	Mechanical-Biological Treatment
K/min	Kelvin per minute	EfW	Energy form Waste
ktpa	kilo tonnes per annum	MCT	Mechanochemical Treatment
ALV	Aerodynamic Lift Velocity	RES	Renewable Energy Sources
MSW	Municipal Solid Waste	ETS	Emission Trading System
WDF	Waste Derived Fuel	LCA	Life Cycle Assessment
EoW	End-of-Waste	SRF	Solid Recovered Fuel
WtE	Waste to Energy	GHG	Green House Gas
RDF	Refuse Derived Fuel	ar	as received

2. Solid Recovered Fuels

2.1. Definition, types, EU and Italian waste legislation

In the EU the classification of fuels from MSW has recently changed with the introduction of several technical documents, mainly in the range of norms UNI CEN/TS 15357–15747, to establish uniform quality standards for the solid fuels produced from wastes for which the name was accepted: "solid recovered fuels" (SRF), also specify as "solid restored fuels" or "solid secondary fuels" (to indicate – per analogy to secondary raw material such as scrap metal, waste paper, or scrap glass – a waste material but with strictly defined chemical and physical properties in accordance with major concept of standardising the SRF). [5] According to norm UNI CEN/TS 15359 *"Solid recovered fuels – specifications and classes"* – that set out definitions, characteristics, sampling methods, parameters of interest and analytical methods, classification, requirements for the quality management system – SRF is the solid fuel prepared (after processing, homogenizing and upgrading to a quality that can be traded amongst producers and users) from high calorific fractions of non-hazardous waste materials to be utilized for energy recovery in incineration or co-incineration plants (intended to be co-fired in coal power plants and industrial furnaces) [6]. SRF cannot comprise fossil fuels. Therefore SRF belong to category "other than hazardous" an its place among other wastes as schematically presented in Fig. 1 (Velis et al., 2010).

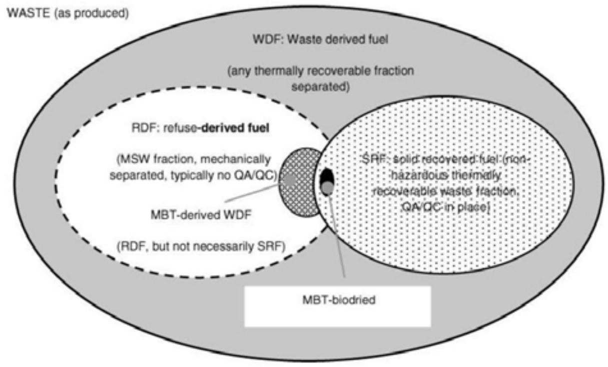

Fig. 1. Venn diagram exemplifying terminology used for thermally recoverable waste fractions in mechanical–biological treatment plants (MBT) and their quality assurance/quality control (QA/QC) (Source: Velis et al., 2010).

In Italy the RDF sector was changed by the issue of the Legislative Decree nr. 205 of December 3, 2010 [7] that established all the characteristics, definitions, sampling methods, parameters of interest and analytical methods for SRF, waste hierarchy fostering SRF production and EoW mechanism (complying to Waste Framework Directive 2008/98/EC [8]). The Decree introduced the definition of "Combustibile Solido Secondario" (CSS) and suggests its utilization in different industrial plants taking into account three main parameters: NCV (economic parameter), chlorine (technologic parameter) and mercury (environmental parameter) content. Each parameter is divided in 5 classes, where the first one is the best and the fifth the worst. Of course the conventional WtE option, i.e. incineration, can be still performed according to more and more stringent regulations. As shown in the Fig. 2 the Ministerial Decree of February 14, 2013 nr.22 (DM 22/2013) defines, in compliance with environmental and health protection standards, the conditions according to which some types of SRF cease to be special waste and are to be considered an "end of waste product" and also regulates its storage, handling and transport. Qualification as waste ceases with the issue of a statement of conformity, classified and characterized according to the UNI EN 15359 Standard [9].

The main principles of DM 22/2013 are: only some SRF types can achieve EoW-status and that also only under specific conditions; SRF production to take place in compliance with waste hierarchy; only certain plants are allowed to produce an EoW SRF (IPPC authorisation/ordinary auth. and EMAS/UNI EN 15358); only certain kind of plants are allowed to use EoW SRF; plants entitled to use EoW-SRF: cement kilns above 500 t/day and power plants above 50 MW of thermal power installed; SRF is still traced during his life time; SRF cannot be stored for an indefinite time; transboundary shipment: EoW-SRF still subject to regulation 1013/2006/UE (waste shipment) according to art. 28. The principles applying to producers are: input to production process: only specific non-dangerous wastes; production process subject to waste legislation; quality management schemes; third parties' control; EoW when declaration of conformity is issued; rules for SRF storage (only within producer's or user's plant). The principles applying to users are: EoW only if used in specific types of IPPC plants; application of former WID/IED (waste) or more restrictive IPPC regulations; rules for transport and storage of SRF within the plant (no storage outside) [10].

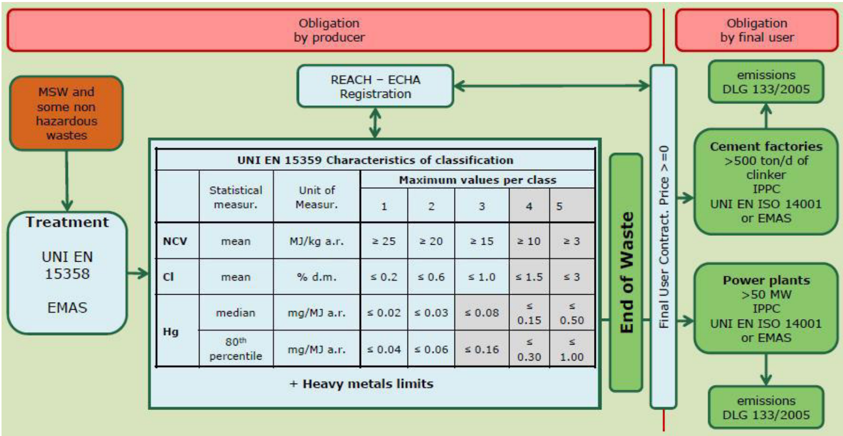

Fig. 2. DM 22/2013 with schematic representation of the conditions for a SRF to be defined as product instead of waste by law (EoW) [11].

2.2. SRF classification

There are 125 SRF classes, based on limit values for three fuel properties:

- the mean value for (NCV; ar).
- the mean value for chlorine content (dry basis).
- the median and 80th percentile values for mercury content (ar).

As shown in Table 1 each properties is divided into five classes by limits values. The SRF is assigned a class number from 1 to 5 for each properties. A combination of the class numbers makes up the class code.

In the SRF classification the parameters are of equal importance and thus non single class number determines the code [12].

Table 1. SRF classification (UNI CEN/TS 15359).

Classification property	Statistical measure	Unit	Classes				
			1	2	3	4	5
Net Calorific Value (NCV)	Average	MJ/kg (ar)	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3
Chlorine content (Cl)	Average	% (d)	≤0.2	≤0.6	≤ 1.0	≤ 1.5	≤ 3.0
Mercury content (Hg)	Median	mg/MJ (ar)	≤0.02	≤0.03	≤0.08	≤0.15	≤0.50
	80th percentile	mg/MJ (ar)	≤0.04	≤0.06	≤0.16	≤0.30	≤1.00

The classification and quality system developed by the UNI EN 15359 for SRF makes it possible to unambiguously classify selected fuel to the concrete class and to specify in great detail its chemical and physical properties which the guarantee to avoid abuses when introducing fuels from wastes into market place [5]. At the same time the system enables the costumers to acquire credible information on SRF quality and the selection of the fuel with certified quality in compliance with technical requirements of plant. Because the industry is looking for alternative fuels in order to save primary fossil fuels, the SRF concept must refer also to specific norms for its industrial use. In the technical norm CEN/TR 15508 information and proposals for the use of SRF in different factories (combustion plants) are given taking into account the SRF key combinations of three properties. The basic idea came from Germany where many plants performed co-combustion activities using RDF/SRF [12].

2.3. Considerations and perspectives about production and use of SRF

The RDF/SRF derived from non-hazardous special waste can come from multiple sources. The most common sources are MSW, commercial and industrial waste (C&IW), construction and demolition waste (C&DW), and/or sewage sludge, plastic-paper fluff (p/p). RDF/SRF can be produced also from the source-separated processed dry combustible fraction, which cannot be used for recycling. Examples of these waste streams are: cardboards drink containers, PE/PET bottles contaminated by PVC, packaging waste, rejects from manufacturing, scrap tyres, discarded biomass, waste textiles, or residues from car dismantling operations [12]. The most common waste materials are paper, plastic, wood and textiles. Another type of waste typically used is the paper fraction (paper+plastic+rubber) from oil filters with high calorific value. SRFs from MSW have generally a lower NCV than the SRFs derived from selected commercial waste, which have a range that corresponds to the NCV of a mixture of biomass and plastic [13]. It is possible to distinguish two major fuel types: shredded or fluff-like material and densified fuels, such as pellets, cubes and briquettes. Densified recovered solid fuel can have NCV i.e. up to 30 MJ/kg depending on composition. Some SRF types have commodity-related quality such as to justify the classification is not as waste but as a genuine product fuel, by virtue of Decree 22/13.

Towards wastes minimization and recovery, Mechanical–Biological Treatment (MBT) plants were constructed in many European Countries for managing ordinary MSW and refers to many combinations of processes. They involve the separation of recyclables from mixed waste either by hand and/or mechanically, and either before or after partial in-vessel composting. They all take place under controlled conditions inside a large industrial building. The main output is a stabilised residue suitable as low grade landfill cover or as secondary fuel for energy-from-waste plants as RDF or in a more refined form as SRF, the final solid alternative fuel produced in a common MBT to SRF plant [14-17]. In Europe, the MBT is an increasing option for the RDF/SRF production for the industrial purposes, but MBT is also pre-treatment before landfilling or combustion in dedicated incinerators. One of the main approaches to directly generate SRF from MSW, involves bio-drying (Rada et al., 2012 [18]; Velis et al., 2010 [16]). In general, a MBT facility can convert 50% of black bag/residual waste to SRF. The typical NCV for SRF is 15 MJ/kg, equivalent to 4.2 MWh/t. For a facility treating 25 t/h of MSW approximately 12.5 t/h of SRF would be produced. Assuming a load factor of 80%, the amount of SRF generated at this rate would be 87500 t/y. The maximum heat available from the EfW facility would approximately be 40 MW. The available heat would depend on the type of technology and electricity production if any. Similarly, a facility with a heat load of 5 MW and operating at 90% utilisation throughout the year would require approximately 16000 tonnes of SRF per year to generate its heat demand [19].

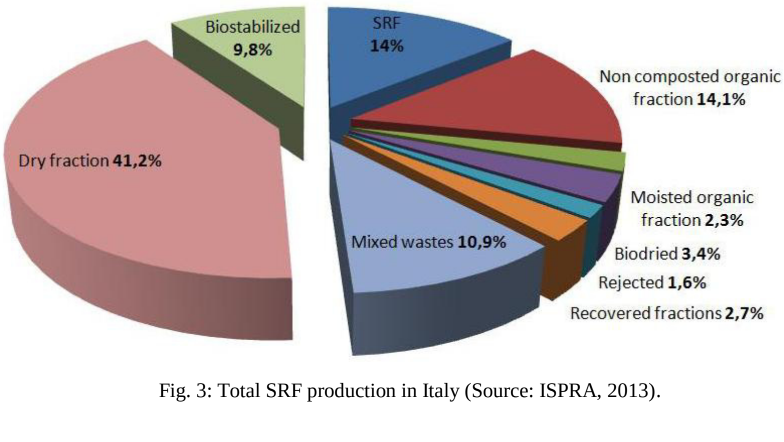

Fig. 3: Total SRF production in Italy (Source: ISPRA, 2013).

In Italy in 2011 were treated in MBT 9 Mt/y of wastes in 122 plants and 8 Mt/y of different fractions are produced. In detail 1.1 Mt/y of SRF are produced (14%, Fig. 3) [20]. The present situation in Italy: in 2011 only 0.18 Mt/y of SRF (not EoW) has gone to Cement Factories and 0.07 Mt/y to Power Plants (Fig. 4).

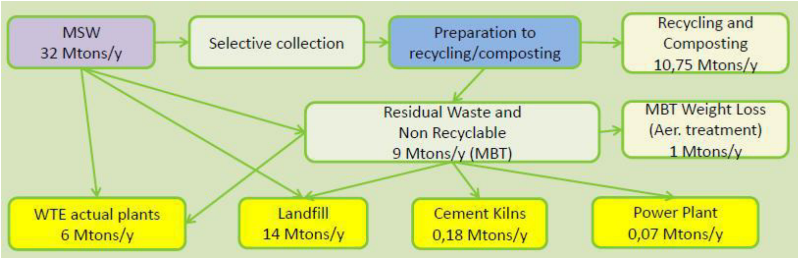

Fig. 4: Co-combustion: present situation [11].

The main attraction of SRF as a fuel-source is that it is considerably cheaper per kWh than fossil fuels. Indeed consumers may want a “gate fee” to use it. SRF can be used as an alternative fuel source in many sectors delivering energy to industry and/or municipalities [19]:

- *Solid fuel power generation*: partial replacement of existing solid fuel with SRF, including existing coal-fired power stations plus smaller wood or bio-mass power stations.
- *Direct solid fuel replacement into existing industry*, most significantly cement industry, lime kilns, industrial boilers and several other industrial sectors.
- *Use of SRF as a fuel source for CHP generation*, ideally located close to process-industrial end-users with large, non-seasonal, low temp (<400°C) heat-load requirements plus power requirements.
- *Use of SRF as a heat-source for large public sector bodies* – prisons, hospitals and Universities, with large non-seasonal heat-requirements.

The use of SRF in these facilities, plus the incinerators, looks like the better integration of the recovery of the "resource" waste after recycling and net of recovery of materials, completing the cycle of industrial development and economic re-sustainable municipal waste and similar, and arriving thereby to establish a virtuous chain of standardization of SRF from MSW, towards the realization of a policy to "Zero Waste" solution.

On the other hand, there are several technical issues that make its use challenging e.g. low energy density and impurities – which ultimately cause pollution emissions of dust, alkali metal chlorides and heavy metals – all of which need controlling.

Overall, in Italy the cost savings of MSW management deriving from SRF chain to the 2020 estimated between 9 and 14%.

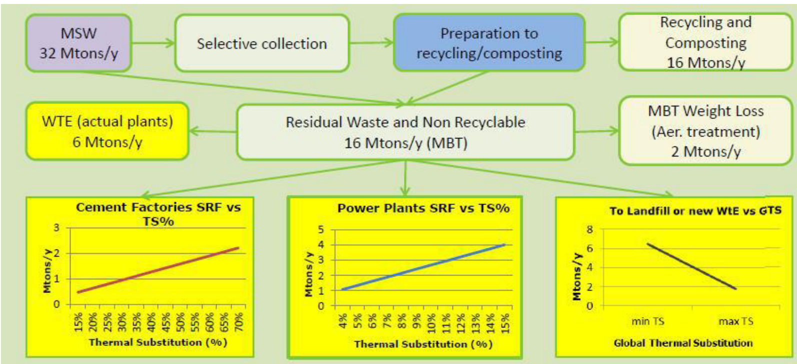

Fig. 5: Co-combustion: scenario at 2020 [11].

The scenarios at 2020 (Fig. 5) is drawn depending on thermal substitution of fossil fuel in cement kilns and power plants and the other assumptions are that: MSW production not changed (ref. 2011); WtE capacity not changed (ref.

2011); Cement factories necessity of fuel not changed and Power plant necessity of fuel 10% reduced (ref. 2012); the target of 50% of recycling is reached as requested by directive 2008/98/EC [11]. Major economic benefits from the SRF production should occur in the regions where the management and disposal of MSW is more critical, such as Campania (34-50%), Calabria (27-40%) and Lazio (24-35 %) [2]. The actual SRF market for co-combustion shows some issues related to low eco-taxation of landfilling, non constant SRF quality, complicate (too long) authorization procedures and low acceptance by population (NIMBY syndrome) with the result that the thermal substitution in the cement industry in Europe is on average about 30%, while in Italy is 8.3% [21]. Moreover, the only about 8% of thermal energy in cement factories comes from alternative fuels (including SRF for 170-180 kt/y) and only one plant (Fusina-Veneto Region) uses SRF (60-70 kt/y). (ref. 2011) [11].

2.4. Benefits of the SRF chain

A SWOT analysis (Table 2) and market drivers analysis (Table 3) allows you to list the major benefits related to production and use of SRF: reduced use of natural resources; avoided use of virgin biomass; reduced dependency on imported fuels; reduction of CO_2 emissions; support to reaching RES objectives; promoting separate collection; reducing disposal; reducing waste taxes; activation of a circular economy; developing high quality recovery industries; fostering consumers' confidence.

Table 2 : SRF EoW - SWOT analysis SRF-synergy.

Strengths	*Weakness*
Free delivery	High cost of production
Coal replacement < prices	Limits in storage and transport
Easier Authorization procedures for the final users	Not enough information about SRF EoW
Maximises local sources of energy and security of supply	Lack of sustained incentives for energy plants to invest in order to handle "waste"
Reduction of waste and less disposal to landfill	Existing EU promotion of WTE has focus on biomass waste
Threats	*Opportunities*
No new landfill allowed	Landfill not enough discouraged
Renewable –fossil resources	Final users not obliged to a not stoppable public service
No public incentives required	Creation strong SRF market
Compatibility with recycling	Adaptation of MSW sorting plants for "energy streams" alongside "recyclables"
Exports of SRF outside EU hinders creation of extensive EU users market	A base for "clean energies"

Table 3 : European overview: SRF market drivers (Source ERFO – European Recovered Fuel Organisation: "SRF Markets", March 2006).

Industry issues	*Drivers*	*Solution provided by SRF*
Landfill directive	Diversion biomass	MSW, with its biomass content, is not disposed in landfill, but recovered as energy
Renewable Energy Sources (RES) Directive	Biomass content	Energy production through SRF co-firing contributes to reach the Directive targets
Best Available Practice	Energy/climate change (Emission Trading Directive)	1 ton of SRF (through its production from MSW and its co-firing) reduces emissions of CO_2 by 1,75 ton/CO_2
Energy cost	Oil/gas/coal, CO_2	SRF has the lowest production cost amongst RES and lowers electricity production costs

Below we summarize energy, environmental and economic benefits in production and use of SRF [22].

1) Energy benefits:

- *High security of fuels supply*, through the promotion of fuel mix.
- *Reducing consumption of primary natural resources*, such as coal or virgin biomass.

- *Use in existing thermal power plants*, considering the widespread social acceptance of new energy projects.
- *Sustainable use of virgin biomass* against market distortions of the foodstuffs market (cereals, corn, etc.) and some important national industrial production (paper, furniture, etc.).
- *Support achievement of the objectives of Directive 2009/28/EC on RES* by virtue of high biomass content.

2) Environmental benefits:

- *Sustainable waste management* can provide cost-effective solutions to criticality in many Italian regions.
- *Integration of the production process with other waste treatment method*, the SRF coming mainly from non-recyclable waste that in practice in Italy is still disposed of by landfilling.
- *Reduction in the cost of cross-border transport of waste*.
- *Greater use of recycling and recovery operations and less use for landfill disposal* (now being depleted).
- *Reduction of CO_2 emissions from landfill and in thermal power plants*, evaluable in 3.86 Mt/y, over the zeroing of fine dusts and substantial reduction of NO_x. The increased interest in this fuel is stimulated also by the ETS for and makes also savings of resources possible.
- *Reduction in GHG emissions* (including mainly CH_4) from depositing wastes comprising biodegradable fractions. Share of these fractions in the SRF can repeatedly exceed 50% by weight. In essence, SRF is not an alternative to other methods of prevention, reduction and recycling, but is an improving option compared to fossil fuel (coal-petcoke).
- *Promoting the development of high-quality recovery industry* to compete in foreign markets generating a greater market confidence in the quality of recovered materials.

Furthermore LCA analyses show that the production and use of SRF from MSW is environmental sustainable option compared to a landfill reference system. The results of LCA study of a 100 ktpa scale UK SRF combustion plant for energy production are compared with those from equivalent scale coal, natural gas and electricity-mix plants (non renewable alternatives). Both scales are economically and technically viable. The SRF plant has a lower Global Warming Potential Emissions (EGWP) compared with the coal, natural gas and electricity-mix plants and the reference landfill system. The SRF plant was found to be an environmentally attractive option quantified at 1540 EGWP compared with coal quantified at 4088 EGWP, natural gas quantified at 2788 EGWP and electricity mix quantified at 6688 EGWP. As a result, SRF combustion is environmentally promising compared with non renewable alternatives. The result showed a lower EGWP for energy recovery compared to landfilling [23].

3) Economic benefits:

- *The SRF chain is economically sustainable and virtuous option.* Landfilling 17 Mt/y of waste is a huge economic loss corresponding to about 3.7 Mtoe equivalent to approximately € 1.8 billion for Italy which shows a strong dependence on energy imports. Evaluating the indifference point of SRF in industrial plants and the costs of wastes currently being supported by local government, it is estimated that the potential savings related to the SRF supply chain are about 40 t/€ as the national average. Overall, the citizens take advantage of the economic benefits of SRF chain for the most part (60-75% depending on the scenario) reducing the cost of waste management for local administrations. The remaining benefits are intended to remunerate the production activity of SRF [2].
- *Savings on "energy bill" and emissions*. In terms of country-system, assuming a national production up to speed of 6.4 Mt of SRF produced from MSW (the actual amount already authorized by the individual regions) would also have a savings of approximately 260 M€/y on energy bills, and a reduction in CO_2 emissions for about 7.9 Mt/y [2].
- *Investments for creating new jobs.* The potential investments in the sector amounted to approximately € 4 billion, and are able to activate employment for over 25000 people over the period of investment.
- *Low management cost of co-firing SRF in power plants.* Co-firing of SRF in coal fired power plants enables the lowest production costs (among RES): it is about 30 €/MWh compared to, for example, 66

€/MWh of hydro technology (small capacity), 121 €/MWh of biomass incineration (with limited biomass availability/calorific value) and 228 €/MWh for MSW incineration – not considering any gate fee for MSW (with consensus problems, NIMBY syndrome) [24].

Detailed technical-economic and environmental analysis of different options to utilize SRF has proved that the options are according their descending attractiveness (assessments for the UK target market): co-combustion with hard coal at cement kilns; co-combustion of the SRF with hard coal at large power plant boilers; incineration at large incineration plants and combustion of the SRFs at large biomass fired boilers. Simultaneously the most financially attractive option has proved to be co-combustion of the SRFs at large power plant boilers [5],[25].

3. Innovative SRF production technology

3.1. Mechanochemical micronization

In order to produce a suitable SRF to the single steam generator, it is necessary to explore new technological frontiers in the manufacturing sector of WDF. The mechanochemical micronization of MSW and waste from mechanical selection of separated collection, is a refining process consisting of chemical and mechanical treatments to be carried out in one continuous cycle plant, able to produce a high-quality SRF. The micronization resulting from the application of an innovative technology of materials processing, the mechanochemical treatment (MCT) [26].

The MCT derives from the experience of the last twenty years on new materials and unconventional metals treatments, which aimed to achieve alloys and ceramic materials with very high resistance, which does not use thermal but mechanical energy transferred to the material through a normal mill which makes a comminution, i.e. a progressive material size reduction of the material. Applied to waste allows to obtain a flowing and homogeneous product, usable as a high-quality solid fuel, from which the dangerous phases, in particular metals and halogens substances harmful to the environment, are easily removed. The innovative idea at the bottom of the micronization is the heat treatment does not concern the waste ar but rather the waste micronized, dried, ground (fluff) and separated from ferrous and non-ferrous metal fractions and other forms of pollutants. Preliminary feasibility studies have demonstrated the real possibility to micronize wastes and in particular some types of waste, using the ultra-mechanochemical comminution technique and at the same time eliminate chlorine salts and metals.

The technical possibilities involve the conversion of the incineration system of WtE plant in the more modern system of disposal/recovery of the materials and energy from waste, integrated with other innovative technologies in order to incinerate SRF namely a product having a high NCV, and produce the maximum possible rate of energy in accordance with the objectives set by the EU, making better use of the waste energy potential [27]. The combustion tests carried out on products prepared with the MCT have yielded very encouraging results, with a NCV which can increase from 14.6 to 23 MJ/kg.

The plant integration is realized through the use of a pre-treatment plant consists of two or more stages of micronization according to a system verified by the DIMA, Department of Mechanical and Aerospace Engineering – Sapienza University of Rome, and the CNR Polymers Department, University of Catania. The above process has been tested in a pilot plant installed at Roccaraso (Province of L’Aquila, Italy).

3.2. Innovative technological installation for SRF production from MBT of MSW

The mechanochemical refining innovative system is placed downstream of the mechanical treatment process of MSW and allows you to transform the pre-treated waste in SRF. It is based on the innovative mechanochemical system, patented and implemented as prototype in Roccaraso. It allows you to obtain a SRF certificate falling into the first three classes defined by norm UNI EN 15359. The waste transformation process consists in the combination of treatments with low-cost physical-chemical methods: thus it reaches the so-called “degree of discharge”, i.e. the smallest dimension within which the waste, or the objective substance, is free from any foreign matter. The micronization is realized through friction and impact actions, putting variable pressures (from 8000 to 15000 atm) so as to destroy the bacterial flora (removing smells and fermentation), and make the product sterile, completely dehydrated (the water is vaporized) and always free from chlorine, sulphates and inert.

With this technology we can obtain a reduction in volume by approximately 70%, a reduction in weight of around 50%, a reduction of the bacterial load and an increase in NCV of waste approximately up to 80%.

From the environmental impact point of view, during processing do not use hot processes, do not use chemical additives (the only possible not channeled emission form is water vapor), does not produce smells or volatile microparticles or dioxin or any kind of pollutant in the air, water and soil, lack of water consumption, do not produce eluates, being treated waste daily.

After harvesting, the current regulations provide that MSW are transferred to suitable facilities treatment. The most common used are mechanical processes (sieving, undersizing, shredding, separation, crushing, screening and picking etc.) with separation of the material recovered from the unsorted fraction before it can be landfilled. In this context downstream of the processing cycles, the system considered is inserted, which allows the transformation of waste treated in SRF, eliminating the bacterial load, reducing humidity to values of around 5% and giving the product a minute and regular geometry, such as to allow appropriate compaction into pellets. Thanks to the capacity of the innovative system to treat not only dry fraction, but also the wet one (with a moisture of 52%), it is possible to adopt a single line for the treatment of MSW with the advantage of being able to treat the indistinctly sorted and unsorted waste with the same operating machineries without the need to use separate lines. The capacity of the line allows you to treating unsorted MSW, treating the recyclables and making SRF.

The technical solution allows you to make the selection on waste ar, with the result of separating dry fraction with high NCV to be sent to the production of SRF, minimizing the amount going to landfill, minimizing the proportion of organic to be disposed of giving the best quality characteristics for subsequent composting and recovering of metals and inert. The technological advantages is to use a single line for the whole process, space and dimensions reduction and electrical loads reduction.

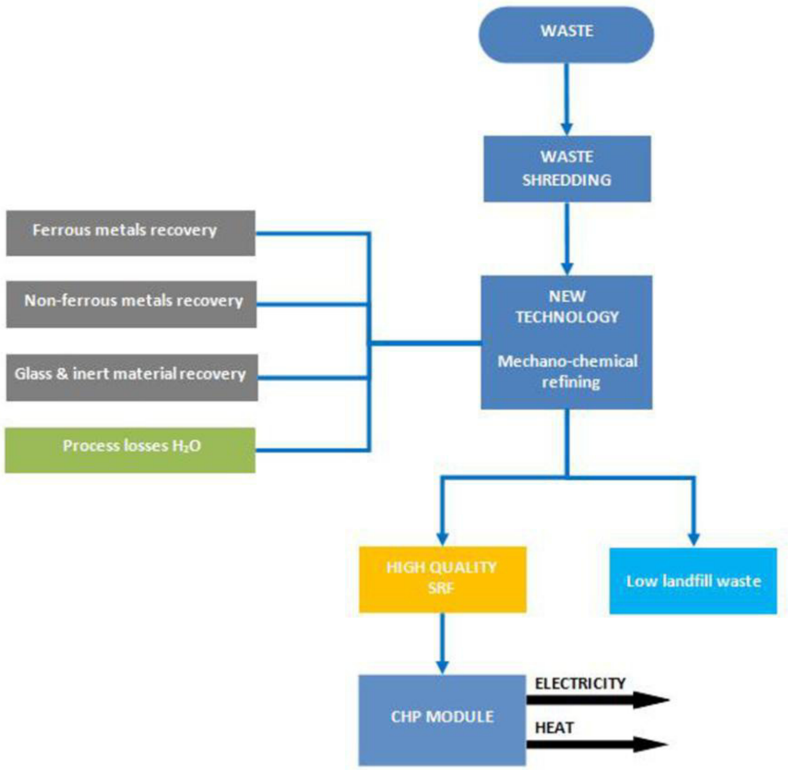

Fig. 6. Integration of the mechanochemical refining system within waste treatment plant.

The block diagram in Fig. 6 shows a summary of the chain of waste you intend to accomplish with the introduction of the system and its "waste". Against the average energy production cost equal to 30 kWh/t, you have a total cost of 15 €/t for size < 1 mm. The carried out combustion tests have shown a good quality for the product in terms of environmental specifications: NCV, Cl and Hg.

4. Experimental tests

4.1. Class determination of SRF produced by MCT

The proposed process, verified by DIMA, increases the energy efficiency of waste, cutting down almost completely pollutants prior to incineration, eliminating in particular the emissions of chlorinated substances and hazardous ash with the use of SRF in the first three classes of DM 22/2013 shown in Table 1.

As reported by norm UNI EN 15359, the study of SRF produced by experimental plant was carried out in a period of 12 months and the test samples were delivered at the ICTP-CNR, University of Catania. The sampling was performed by technical director of the plant. Considering that the plant annual production was about 120 tons, therefore, as required by UNI EN 15359 batch of analyzes was 10% of annual production divided into 12 months of the trial. The comparison between the values of NCV and chlorine with the limits specified for the class listed in the legislation is done referring to the confidence interval to 95% of the average of ten measurements. To determine the lower and upper limit of the confidence interval of the arithmetic mean the following equation is used:

$$X = \overline{X} \pm 1{,}96\sigma(n)$$

Wherein:

- X lower/upper limit confidence interval of 95% of arithmetic mean.
- $\overline{X}$ arithmetic mean.
- 1,96 number characteristic of normal distribution (for the confidence interval at 95%).
- σ standard deviation (based on all sizes).
- n number of measures (in this case n=10).

According to norm UNI EN 15359 the value of NCV to be used to characterize the lower limit of the confidence interval to 95% of the average. For chlorine is to be considered instead of the upper value of the mean at 95% confidence interval. From the carried out analysis the values of the three properties required for classification of SRF have been extracted in Table 4. The values obtained from calculations to SRF classification are displayed in Table 5:

Table 4: Summary table of extracted data from the test reports of the experimental analysis on the samples from the plant. The samples are numbered for increasing value of Hg.

	1	2	3	4	5	6	7	8	9	10
NCV (MJ/Kg)	13.81	14.91	18.64	17.00	17.00	15.91	15.40	14.50	15.62	13.00
Cl (%)	0.17	0.38	0.35	0.46	0.43	0.32	0.28	0.34	0.30	0.46
Hg (mg/MJ)	0.001	0.001	0.002	0.011	0.011	0.013	0.017	0.020	0.030	0.046

Table 5: results of the calculations to SRF classification.

	Average	Standard deviation	Upper limit	Lower limit	Median	80th percentile
NCV (MJ/Kg)	16	1.58	-	15	-	-
Cl (%)	0.4	0.10	0.4	-	-	-
Hg (mg/MJ)	-	-	-	-	0.01	0.03

It is possible to classify the SRF produced in this trial with the SRF classification code: NCV 3, Cl 2, Hg 1. The NCV (the economic parameter, as specified), throughout the experiment amounted on a mean value. However, this result is a positive result because it must be remembered that the material in input to the process line plant is an unsorted MSW containing the organic fraction (wet). The test showed some problems, first of all the location of the plant, placed in a tensile structure and then exposed to adverse weather conditions (Roccaraso is a place with cold climate) without a suitable site to store the SRF produced. This implies that the SRF absorbs significant amounts of water. Nevertheless, the results obtained are satisfactory. In this study it was intended to take average values for SRF, then the input material has not been previously selected. It is understood that through the selection of MSW, non-selected, entering the plant is possible to vary some fundamental parameters including NCV, particle size, chlorine and mercury values.

As reference the SRF produced at the Herambiente plant of Ravenna, during the procedure for the release of the IPPC permit, in the analytical campaign (end 2012-march 2013) carried out the output streams (CSS1/CSS2/CSS3) from lines 1,2 and 3 have been sampled and analysed. CSS1 is classified: 4.3.1, CSS 2 is classified 5.3.1 and CSS 3 is classified 4.2.1. Moreover, the old RDF produced in the plant of Ravenna complies with the SRF classification (EN 15359) and could be classified as SRF 2.3.2. The net calorific value ranges from 13900 to 22700 kJ/kg, showing high values in the central months of the year [28].

4.2. Results of the analysis conducted on samples of WDF

This section discusses the results of the analysis carried out on three samples of WDF that were analyzed for the determination of their combustion properties, heat capacity and emissions. The following analyses were suggested: proximate analysis; calorific value determination, thermo-gravimetric analysis and Gas Chromatograph analysis. For the sake of comparison, a coal sample and a biomass (pine dust) sample were analyzed along with the WDF samples.

The samples are described as outlined by Table 6.

Table 6: Description of samples.

Sample name	Mass	Description	Presentation
1	138g	Feed material: Fluffy waste material mixed with small pieces of plastic paper.	
2	210g	Middle material: Very small semi pellet sized material with visiblesmall pieces of plastic.	
3	180g	Pellets: Approximately 1cm long pellets of 0.5 cm diameter.	

The methodology requires as first step to the experimental analysis a size reduction. The samples were pulverized into fine powders after randomly sampling approximately 30g of each material. After pulverizing, the plastic material contained in the sample, particularly sample 2, was merely thinned out but remained intact. Since most of the sample was pulverized, it was assumed that the pulverized material is a good representation of the whole sample.

The GCVs of the samples were determined by the use of a Dry Cal bomb calorimeter and displayed in Table 7. A decrease in the calorific value is noted from samples 1 to 3. When compared to that of coal, the calorific values of the WDF samples are relatively low. The calorific value of samples is comparable to that of the biomass.

Table 7: Gross Calorific Values.

Sample	1	2	3	Coal	Pine
Gross Calorific value (kJ/kg)	20.399	17.689	14.394	28.22	18.12
	20.245	17.655	14.570	28.07	18.64
	20.445	17.864	14.540	28.08	18.82
Average GCV (kJ/kg)	20.363	17.726	14.501	28.12	18.52

The *proximate analysis* results for the 3 WDF samples and the coal sample are displayed on Table 8. Minor changes in the WDF sample moisture values are observed. A decrease in volatile matter from sample 1 to 3 is noted, and conversely the fixed carbon increases. The ash content shows consistency for samples 1 and 2, a notable increase in the ash content is noted for sample 3. On comparison to the coal sample, the RDF samples have significantly higher volatile matter, and a lower fixed carbon content. The WDF samples have a notably higher ash content than the coal sample analyzed (a washed South African Witbank coal). On comparison to the biomass sample, the WDF samples have comparable fixed carbon to that of the biomass. The biomass however presents a higher volatile matter and moisture content than the samples analyzed. The biomass also has a very low ash content.

Table 8: Proximate analysis results.

sample	Moisture	Volatiles	Fixed carbon	Ash
1	2.54	68.04	6.51	22.92
2	1.67	63.35	13.63	21.35
3	2.05	53.79	13.57	30.59
Coal	2.95	35.70	49.18	12.18
Pine	7.45	78.29	14.06	0.21

Non isothermal analyses were carried out at a heating rate of 15 K/min where maximum burning rates R_{max} (% weight fraction/min^{-1}) that has been measured. The maximum burning rate Rmax has been considered directly proportional to the reactivity of the sample (Gil et al., 2010 [29]; Zheng and Koziǹski, 2000 [30]). The R_{max} value was used in this analysis for comparison of the sample reactivity. The combustion properties for each sample are displayed on Table 9. The corresponding temperatures of maximum burning rates (T_{max} (K)) are available upon request.

Table 9: Combustion Analysis. R_{max} Values.

sample	Rmax (% mass fraction remaining/min)
1	6.26
2	7.75
3	6.06
Coal	13.79
Pine	26.05

An increase in the maximum reactivity (24%), is observed on sample 2 from sample 1. Sample 1 and 3 present very similar rates of maximum reactivity. For coal, the R_{max} for the coal is much higher than that of the RDF fuels (120% increase in R_{max} when compared to the R_{max} of sample 1). The biomass sample presents an even higher R_{max} value than that of the WDF samples (316% increase in R_{max} when compared to the R_{max} of sample 1).

The GCV of the WDF samples are relatively lower than that of coal and comparable to that of the biomass sample analyzed. The GCVs and volatile content of the samples decrease from sample 1 to 3. A notable increase in the ash content is observed on sample 3, whereas samples 1 and 2 show relatively lower and consistent ash content values. On comparison to the coal sample, the WDF samples have significantly higher volatile matter, and lower fixed carbon content. The WDF samples have higher ash content than the coal sample analyzed, however, the ash content of most South African coals is well within the range of that observed in the WDF samples. The biomass sample has a higher volatile content than that of the WDF samples as well as lower ash content and higher moisture content. The fixed carbon contents of the WDF samples are comparable to that of the biomass sample. An increase in R_{max} of 24%

is observed in sample 2, whereas a decrease in R_{max} of 3% in sample 3 when compared to that of sample 1 is observed. While the coal sample presents an increase of 120% in R_{max} when compared to that of sample 1, the biomass presents an increase of 310% to that of sample 1.

5. Design of SRF specifications for energy enhancement in power plants

5.1. Use of SRF features in thermal power plant

The co-combustion of SRF with the conventional fuel (e.g. coal) in thermal power plants currently in a variable percentage (usually low) is an economically attractive option in replacing regular fuels. The higher efficiency of power plants results in a better utilization of the CV of SRF than MSW incineration. However, extensive investigations on the combustion behaviour of SRF in the boiler should be performed, since even hiqh-quality SRF, in combination with the high parameters of the steam, can produce corrosion issues in the boiler elements. To have equivalent performance SRF has to be manageable during storage, handling and feeding of the burners in at the same way that other traditional fuel. In this case, the key parameters are moisture, size and homogeneity of the various fractions or, more in general, the rheological characteristics of the material.

5.2. Cocombustion in coal-fired power plants: experiences in EU and Italy

The co-combustion (or co-incineration) of pre-treated waste-derived fuels such as SRF describes their combustion in industrial furnaces or power plants as a supplement fuel to replace a certain amount of the regular fossil fuel (coal, oil, gas) mainly because of economic reasons. In respect to the closed combustion system of a power plant, where coal is combusted and not incinerated, the term “co-combustion” is applied for SRF, accordingly. Complying with the emissions and air quality control directives, co-combustion of SRF can be an efficient and low-cost form of energetic and material exploitation. The high biomass content of SRF (usually > 50%) is an additional means to use a substantial potential in a highly-efficient and cost-effective way in a power generation, thus making a lasting contribution to CO_2 emission reduction and resource saving [31]. Co-firing of SRF with fossil fuels in utility boilers is feasible for limited fractions (up to 10%) of SRF [16], [32]. Currently the main SRF users are found in the cement, lime industry and paper mills. The coal fired power plants can be assessed as an emerging sector with huge potential. Co-firing SRF in energy production units throughout Europe, even in small thermal shares, offers enormous potential as a sustainable, efficient and environmentally friendly waste-to-energy technology [33].

SRF can be co-fired with coal in commercial pulverised coal power plants: pulverised coal furnaces are applied in boilers with stream capacities from 20 kg/s to the biggest ones. Coal is burnt after the preliminary drying and pulverising. Residence time of coal particles in the zone of combustion is equal to several seconds. Unburned coal particles are carried over with the flue gases (fly-ash) or fall down to the combustion chamber slag hopper (slag). Temperature of combustion in pulverised coal boilers ranges from 1200 to 1400 °C but air (flue gas) velocity is higher than 9.1 m/s [5].

Experience with SRF in the EU. Despite the technical challenges the co-combustion of SRF with peat, wood pellets or other biomass material (including WDF) has gained interest in many European countries. The European recent experience of SRF use for electricity generation is mainly restricted to small-scale plants in Germany, The Netherlands, Italy and the UK [34]. The EU funded project RECOFUEL [35] (started in 2004) has been a considerable EU research program to investigate the potential use of WDF in large-scale coal-fired power plants. Requirements vary according to plant design and coal type but are generally higher than alternative options for RDF/SRF thermal recovery [36]. SRF which contains plastics and paperboard from packaging materials generally has a higher net calorific value, often from 15 to 25 MJ/kg (4.2–7.0 MWh/t). Such SRF can function as a support fuel, improving ignition, contributing to more stable combustion and superior burn out of low-grade biofuels (and also of peat). However, most SRFs contain considerable amounts of sodium and chlorine, some potassium, and similar amounts (but different species) of heavy metals when compared to solid fossil fuels and biofuels [37].

In Germany RECOFUEL project demonstrated the co-combustion of SRF with brown coal in two commercial scale pulverised fuel boilers at RWE Power’s power plant site in Weisweiler. The pre-trial focused mainly on fuel handling, conveying and feeding issues while monitoring the burning and changes in emissions. The SRF content was varied between 2% and 8.5% and with a heating value of 25.4 MJ/kg is almost double that of Rheinish brown coal. The SRF was added with an existing paper sludge handling system. The test result showed no significant operational problems, and a small increase in power production was seen due to the higher heating value of SRF/coal mixture. There were no changes in flue gas emissions and the amount of unburnt fuel in the wet bottom ash was negligible. There were small changes in NO_x and CO, which could be attributed to the brown coal quality [38]. The Janschwalde brown coal power plant (BCPP) uses SRF at an average calculated substitution rate of 1.8% w/w, without any significant impact on operational performance and emissions. Presently, there are at least 9 pulverised power stations in Germany, both lignite and hard coal that have performed or are conducting co-firing (e.g. SRF is used in the following power plants: hard coal, RWE Gerstein, 220 kt/a; lignite, Vattenfall Jänschwalde, 400 kt/a; lignite, RWE Berrenrath, 70 kt/a) [33], [39].

In Finnish energy production, SRF is co-combusted with wood and peat. It has been found that the co-combustion of SRF increases maintenance requirements of boilers and hence operational cost. Furthermore, feeding requirements and flue gas cleaning systems would also require additional investment to enable emissions to be closely monitored [40].

In Italy there are 13 coal power plants with 9700 MW of e.e. capacity required in 2012 about 19 Mt of coal [11]. In the coal power plant located in Fusina-Venice owned by ENEL, RDF (produced by Ecoprogetto) is successfully co-fired with hard coal up to 5% of thermal input with low emissions and high thermal efficiency (35%) which is roughly 40% higher than a dedicated RDF power plant (ENEL, 2010). The unit is equipped with a tangential fired dry-bottom boiler with LNCFS (Concentric Firing System). A study was carried out by 3D-CFD code IPSE in order to evaluate separate RDF injection in 320 MW_{el} Unit 4 of ENEL "Andrea Palladio" co-firing thermoelectric power plant for co-firing asset 5%th RDF-95%th hard coal (co-firing asset: bituminous coal + 5% of RDF since 2009; 70 kt/y of RDF, RDF mass flow/unit: ave. 6.7 t/h, max. 9.2 t/h; ave. hRDF/hfire=72%; power plant index of e.e. production: 1.7 MWh/t of SRF). Currently about 70 kt/y of SRF are sent to the ENEL facility, but this is expected to increase to 100-105 kt/y. It takes 2 tons of SRF to generate electricity to power a home users for a year. For every ton of SRF used in co-firing is avoided the production of 500 kg of CO_2. The code, developed by ENEL, has been extensively used for the analysis, design and process optimisation of combustion systems for industrial steam generators. The code was validated with experimental measurements [41], [42].

After a pluriannual research, the SRF is currently used in 2 sections of the plant, with 320 MW_{el} of power each. The site has a small plant for the receiving, shredding, and transfer of the SRF by pneumatic transport. Is very important that the SRF can be shredding up (dried and non sticky) to pulverize to 3 mm. Four long-term (8-15 months) boiler corrosion monitoring campaigns performed (two into the combustion chamber and two in the convective pass) were carried out in RDF-coal co-firing Fusina PP by *RSE corrosion monitoring sy*stem, exposing samples in the current operating conditions or simulating the operation in co-firing+Ultra Super Critical steam cycle. Tested steels S304H and 347H (currently used in the plant) in the convective pass showed a negligible corrosion both in the current and USC conditions on the contrary tested steels 16Mo3 and A105 (currently used in the plant) at the membrane wall indicated that fireside corrosion was depending on the probe position, generally higher close to RDF-coal nozzles; estimated long-term 16Mo3 consumption in co-combustion operation was higher compared to that one for operation with coal as fuel. The long-term campaigns also showed that on-line measurements of material consumption can supply the plant managers with relevant and timely information on material degradation in different operating conditions useful for the optimization, which are in good agreement with post-exposure metallographic examinations (Fantini et al. 2010 [43]).

5.3. Main technical and environmental issues in the cocombustion of SRF in the waste fired boilers

The CV of SRF, hence its energy density, is low compared with fossil fuels. Moreover, solid fuels contain moisture i.e. water, as well as some sulphur, chlorine and ash components. Solid bio-fuels usually have high moisture contents, between 10 and 60 %, and high oxygen content, thus low NCV, typically between 5 and 15 MJ/kg (1.4–4.2 MWh/t – i.e. less than half that of coal).

Despite of un-doubtful ecological benefits deriving from using SRF in the energy sector it was found out however those not beneficial phenomena of erosion-corrosion occur during boilers operation. Burning SRF would also require scrubbers to meet air pollution standards and would increase maintenance levels. There is also a higher risk of corrosion and failure of the boiler super heaters.

The Specific technical and environmental issues with SRF quality during direct co-combustion with various types of coal in different boiler technologies have been identified:

- *Air emissions and air pollution control*. It may prove difficult to control emissions of highly volatile trace elements, such as Hg, Cd, and Tl [44].
- *Airborne particulate matter*. Initial results from test runs of RECOFUEL project at the Weisweiler RWE power plant, cocombusting Rheinish brown coal with low NCV (8.15 MJ/kg) with RDF/SRF of higher NCV (15.4 MJ/kg; REMONDIS SBSR® produced from sorting of residual MSW) at relatively high thermal substitution rate (8.5% of overall thermal input) showed no significant changes of the flue gas emissions that could be allocated to the SRF use.
- *Quality of marketable by-products*. Concerns have been expressed regarding the potentially adverse impact on the quality of marketable byproducts; that is, boiler ash, pulverized fly ash (PFA), and gypsum. Their chemical, physical, and mineralogical properties may be affected.
- *Plant operation*. WDFs have lower softening point (SP) and melting point (MP) temperatures than coal, resulting in an increased scaling or corrosion potential. The corrosion potential is enhanced by a lower S content, higher alkali, and higher trace elements of concern, estimated as low for S/Cl > 4 and as high for S/Cl < 2,78 (Beckmann and Thom´e-Kozmiensky [45]). Hence, the Cl concentration of the overall fuel mixture should be restricted to prevent high temperature corrosion. Design and construction materials of the boiler affect the maximum allowable Cl content, estimated to be up to 0.2% w/w in The Netherlands and 0.4% w/w in the UK. Alkali metals become molten at combustion temperatures (slagging), increasing the risk of accumulation of fused deposits on the heat transfer surfaces (fouling). Abrasive RDF/SRF constituents, such as grit and glass particulates, may erode the heat transfer tubes. Heavy wooden and plastic compounds even at particle size of 20 mm exhibit different combustion behavior than pulverized hard coal and have to be separated out. A higher moisture content of SRF (10–20% wt.) compared with that of coal (ca. 5% w/w) could result in increased gas water content and subsequently increased gas volume in the boiler, restricting the substitution rate of SRF to 5–10% w/w [36].

In waste fired boilers high temperature corrosion has often been attributed to zinc and lead chlorides. In addition, bromine induced high temperature corrosion has been earlier observed e.g. in a bubbling fluidized bed (BFB) boiler co-firing SRF with bark and wastewater sludge. It was observed that Cl, Br, Zn and Pb originate to a large extent from the SRF, they are vaporised in the furnace, and may form waterwall deposits. This, complemented by fluctuations between oxidising and reducing atmosphere resulted in rapid corrosion of the waterwall tubes.

Chlorine. There is a general agreement that Cl in SRF originates mainly from chlorinated plastics, mainly polyvinylchloride (PVC), or food residues which contain dietary salt. Approximately 70% of the Cl in MSW has been estimated to originate from plastics, particularly PVC. In addition to PVC, chlorine is used in flame retardants. Plastic materials are the main sources of chlorine in SRF. Chlorine is attributed to be the main initiator of slagging, fouling and corrosion in biomass and waste combustion as it lowers the MP of ash forming matter and reacts chemically with the heat transfer surface steels [46], [47].

Bromine. It has been shown that SRF typically comprises of 35–50% textiles and plastics. Therefore, the likely sources of bromine in solid wastes are brominated flame retardants (BFRs). Brominated compounds are used in both commercial and residential water treatment which can be a source of Br in both industrial and municipal sewage.

Firing or co-firing of biomass and RDF/SRF in efficient power plants can lead to high-temperature corrosion of superheaters due to condensation of alkali chlorides into superheater deposits. Corrosion can be prevented if a significant portion of the alkali chlorides present in the flue gases is destroyed before reaching the superheaters.

5.4. Functional parameters of SRF for use in power plants

To make SRF useful for a specific combustion system (e.g, pulverised firing system, grate firing, fluidised bed or cement kiln) standard analyses of the SRF will determine basic parameters about the combustible and incombustible matter. The amount of energy, the content of water, volatiles, fixed-carbon, ash, and particle size will roughly dictate the type of combustion system that is best suite. However, vital information on the SRF with respect to the following which is needed to determine the combustion behaviour in real boilers will requires additional tests [48].

The quality parameters and the physical-chemical characteristics make SRF produced with the mechanochemical micronization suitable for use as fuel in thermal power plants. By a focused selection of the input material, it is possible to achieve default values for a set of parameters such as NCV, particle size, moisture content, etc. In particular, it is necessary to check the quality parameters, which must be remain stable over time, and the physical-chemical characteristics that make it usable in power plants as a alternative fuel to replace conventional fuel (such as coal or petcoke). The equivalence between SRF and conventional fuel (such as to allow its use in steam generators) is identified by a complex set of physical parameters, in particular with regard to:

- *NCV (MJ/kg ar).* SRFs from MSW have generally a lower NCV than the SRFs derived from selected commercial waste, which have a range that corresponds to the NCV of a mixture of biomass and plastic. Densified recovered solid fuel can have NCV i.e. up to 30 MJ/kg depending on composition. The NCV of the SRF (also if in first class according to DM 22/2013) can reach the value of about one fifth lower than coal (i.e. equal to about 27 MJ/kg, being the NCV of bituminous coal – the most well-known, widely used and fossil fuel – between 33 and 38 MJ/kg). This lower value is still economically and environmentally very convenient for three essential reasons: the cost of SRF is equal to a one fifth of the current price of coal, SRF obtains the contributions of Environmental Certificates linked to the use of biomass and sensitive improvements of some environmental parameters. This means that current technologies can produce an SRF based on the needs of each individual system.
- *Maximum particle size for complete combustion.* The particle size of WDFs is an important parameter because it characterizes the conditions of possible use of the SRF. In its final consistency the SRF can occur in various forms, more or less thickened: powder < 1 mm, fluff, similar to coriander of various sizes, more dense forms as cubes, pellets, briquettes or in granular form. There are currently SRF manufacturing technologies can provide a new product (powder on 3 mm). In particular in thermal power plants it may be provided the use in different formats or sizes: loading directly pulverized SRF into the boiler (obtainable with a particle size < 3 mm); use in pellet format (format that ensures greater ease of movement and storage in power plants); use through gasification process for power plants that run on natural gas and/or multi-fuel. A study shows that the SRF with an equivalent median diameter D_{50} of 6.8 mm are to be directly co-fired in an existing pulverised coal power plant. In comparison to pulverised coal the particle size distribution of SRF is of several magnitudes higher resulting in a different burnout behaviour. Size reduction of SRF to a fraction similar to coal is not economically feasible. Therefore care should be taken to a suitable size reduction to avoid the risk of incomplete combustion [49].

To predict the burner injection levels of SRF and whether or not a complete combustion will be achieved under full and part load conditions to forecast the success of co-firing the SRF in a commercial pulverised coal power plant, it occurs to carry out analysis of fuel and its intermediate chars, generated at conditions comparable to boiler conditions, to determine some characteristic parameters:

- *Aerodinamic Lift Velocity (ALV) of the SRF particle .*
- *Burnout time (BT) of the SRF particle.*
- *Apparent densities.*

The values of this parameters can be correlated to boiler conditions to determine the possible distances they are likely to travel under various regimes, full load and part load, to determine the optimal boiler injection points. Other important parameter to evaluate to maximize the performance of SRF in combustion systems are:

- *Reactivity.*
- *Residence time for complete combustion*.

A study of the performances of a 680 MW_{el} pulverised hard coal boiler shows that the conditions in different boilers can easily be correlated with the parameters, particle BT and ALV, to avoid incomplete combustion. These parameters are essential characters that could describe the combustion behaviour of SRF in a pulverised firing system. With large particles > 2 mm used in pulverised fuel fired system considered drop-tube furnaces or any other technical scale combustion furnace show serious limitations as the particles fall through it without even completing de-volatilization [49],[50].

5.5. Designing specifications for SRF

To obtain high-quality SRF is necessary to check input material, in particular its NCV, chemical and physical properties. The structure of SRF fuel can be controlled, since such material is obtained by mixing different waste fractions with known properties – by preliminary laboratory analysis carried out – and one can design a product, with a known composition of diverse waste materials.

The set of norms UNI EN relating to SRF is strictly aimed to assess and encode the chemical-physical properties and commodity-related features that SRF must have to perfectly replace conventional fuels in combustion process such as coal in industrial and energy intensive power plants.

The characteristics of SRF concern:

- *Composition*: description of the component materials.
- *Physico-chemical properties*: melting point, density, solubility, mean diameter by volume, flash point, ignition temperature, oxidising properties.

The study pays particular attention to the product standardization according to the operating parameters of the steam generator, with the aim of making SRF a designed product for the particular requirements of the system (having feature of "specification" for the system) to the aim of obtaining consistent performance and strict emissions control. The auditing activities are intended to unambiguously define the operation parameters of the installations and its modulation and control limits. Following these activities, the auditing process provides in feedback necessary data to design the fuel parameters and specifications: NCV optimum, appropriate particle size and best composition/physico-chemical properties to improve energy performance of SRF and, at the same time, minimize the phenomena of corrosion and damage of the plant components and zero the emissions.

The study has the ambitious goal of defining useful guidelines to the design of a standardized SRF according to the characteristics and parameters of power plant operation that is subject to predefined specifications, to finally get a SRF custom designed for the specific plant (as a "system parameter").

5.6. Design methodology for the use of SRF in conventional power plants

The evaluation of the potential of SRF compared to conventional fossil fuels is performed by a preliminary assessment of the system and its operating features. The logical process is organized as follows:

1) *Acquisition of information on the existing state (auditing)*.

2) *Experiments and numerical simulations by modelling plant systems*.

3) *Preliminary and detailed design of the functional equipment required for the conversion project*.

For each plant technical and economic pre-feasibility studies on the conversion must be done through:

- Revamping of thermal section in order to use SRF.
- Definition of the necessary measures to restore function to the general operation of the plant.
- Detailed definition of the planned interventions.
- Preparation of business plans.
- Detailed design of interventions.
- Revision/elaboration of studies and environmental impact permissions (SIA: strategic environmental authorization; AIA: integrated environmental authorization).

Possible extraordinary maintenance function to the proposed changes may include the following major components: boiler, combustion chamber, loading system and the other main equipment.

By admitting the possibility to standardize the parameters of SRF is likely to consider that, whereas an average NCV equal to half than coal, there is a ratio of one third. Then this could be the yardstick against which choked the thermal power of existing plants.

6. Conclusions

Several conclusions are drawn from the analysis presented. The recent European policy on wastes focused on an effective environmental protection and sustainability, a lot of restrictions concerning MSW disposal were introduced in the European Lawn to minimize the pollution through the use of promising methods realizing the most effective use of resources with minimum environmental impact (realizing a Sustainable Waste Management system). In this context the SRF appears a low-cost renewable energy source that could be used replacing fossil fuels as an alternative in energy intensive operations, such as thermal power plants. The careful selection of the treatment processes is of primary importance both from the economical, environmental and energy recovery point of view. SRF should be produced should be from residual streams resulting after the application of extensive source recycling and composting Plastic recovery for recycling, by mechanical pre-treatment before energy recovery, supported similar or increased energy savings, compared to full stream mass combustion. The application of an integrated MSW management will effectively meet the goals of sustainable development, environmental protection (as demonstrated by LCA study shows that energy from SRF is an environmentally promising way of managing waste, while helping achieve renewable energy targets), industrial ecology and industrial co-existence.

The co-combustion of SRF with coal in thermal power plants are investigated. This has proved an profitable and cost-effective solution if compared to MSW incineration and biomass combustion. From a financial perspective, co-combustion in power plants is potentially the most profitable option and when SRF streams were used in coal-fired plants, the energy balance of these systems improved substantially.

The correct design of the SRF specifications allows you to satisfy the plant operating conditions and increasing the potential of thermal substitution. For this purpose, the mechanochemical micronization represents the best innovative technique to produce high quality SRF to be used in thermoelectric power plants in partial substitution of the conventional fossil fuels.

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