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Combining plasma gasification and solid oxide cell technologies in advanced power plants for waste to energy and electric energy storage applications

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ABSTRACT

The waste to energy (WtE) facilities and the renewable energy storage systems have a strategic role in the promotion of the "eco-innovation", an emerging priority in the European Union.

This paper aims to propose advanced plant configurations in which waste to energy plants and electric energy storage systems from intermittent renewable sources are combined for obtaining more efficient and clean energy solutions in accordance with the "eco-innovation" approach.

The advanced plant configurations consist of an electric energy storage (EES) section based on a solid oxide electrolyzer (SOEC), a waste gasification section based on the plasma technology and a power generation section based on a solid oxide fuel cell (SOFC). The plant configurations differ for the utilization of electrolytic hydrogen and oxygen in the plasma gasification section and in the power generation section. In the first plant configuration IAPGFC (Integrated Air Plasma Gasification Fuel Cell), the renewable oxygen enriches the air stream, that is used as plasma gas in the gasification section, and the renewable hydrogen is used to enrich the anodic stream of the SOFC in the power generation section. In the second plant configuration IHPGFC (Integrated Hydrogen Plasma Gasification Fuel Cell) the renewable hydrogen is used as plasma gas in the plasma gasification section, and the renewable oxygen is used to enrich the cathodic stream of the SOFC in the power generation section. The analysis has been carried out by using numerical models for predicting and comparing the systems performances in terms of electric efficiency and capability in realizing the waste to energy and the electric energy storage of renewable sources. Results have highlighted that the electric efficiency is very high for all configurations (35–45%) and, thanks to the combination with the waste to energy technology, the storage efficiencies are very attractive (in the range 72–92%).

1. Background and scope

The waste management is become a very crucial issue in many countries, due to the ever- increasing amount of waste material, both domiciliary and industrial, generated.

Together with prevention and recycling measures, waste to energy (WtE) facilities contribute significantly to reaching the goals of waste management (Brunner and Rechberger, 2015).

The research of most effective and environment friendly technologies for the solid waste treatment for energy purpose is a key issue for promoting the "eco-innovation", that means "invention, innovation and diffusion", according to the definition of the European Environmental Agency (EEA).

The eco-innovation and, as a consequence, the sustainable development are also linked to the increasing of the share of renewables in the energy mix. Renewable energy sources, like solar and wind, have a great potential, but their utilization is difficult due to their fluctuating and intermittent nature. Thus, storage solutions must be implemented in order to satisfy the demand and to valorize each kW renewably produced (De Saint et al., 2014).

The study proposed in this paper aims to assess the performances of advanced plant configurations in which waste to energy plants and electric energy storage systems from intermittent renewable sources are combined for obtaining more efficient and clean energy solutions as required by the "eco-innovation" approach. Thus, the novelty of this study consists in combining WtE facilities with EES systems from intermittent renewable sources.

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Nomenclature

MSW	Municipal Solid Waste	ASU	Air Separation Unit
RDF	Refuse Derived Fuel	DC	Direct Current
IAPGFC	Integrated Air Plasma Gasification Fuel Cell	AC	Alternating Current
IHPGFC	Integrated Hydrogen Plasma Gasification Fuel Cell	CHP	Combined Heat and Power
SOFC	Solid Oxide Fuel Cell	WGS	Water Gas Shift
SOEC	Solid Oxide Electrolysis Cell	PCBs	Polychlorobiphenyls
FC	Fuel Cell	PG	Plasma Gasifier
EC	Electrolysis Cell	HHV	High Heating Value
WtE	Waste to Energy	HTZ	High Temperature Zone
EES	Electric Energy Storage	MTZ	Medium Temperature Zone
WTRP	Wind Turbine Rated Power	LTZ	Low Temperature Zone
CAES	Compressed Air Energy Storage	LHV	Low Heating Value

Each plant configuration consists of three main sections whose integration depends on energy and mass fluxes from and to one another: (1) the *renewable and storage section* based on a solid oxide electrolyzer, (2) the *plasma gasification section* based on the plasma technology, (3) the *power generation section* based on a solid oxide fuel cell.

This study has been conducted by using a numerical approach based on the development of thermochemical and electrochemical models, able to predict the behavior of each section of the proposed advanced power plants.

These models have been calibrated to reproduce the operating conditions and the performances of the electrolyzer (Perna et al., 2016a), the fuel cell (Minutillo et al., 2014) and the plasma torch gasifier (Perna et al., 2016b), according to the data collected from considered publications or companies' websites.

By calculating mass flows, compositions and thermodynamic conditions (pressure, temperature, enthalpy, etc.) at the inlet and outlet of the components in each section, the numerical models have allowed to estimate the power output, the electric efficiency, the cogeneration efficiency and the storage efficiency.

1.1. Waste management and plasma gasification technology

The waste management policies of the European Union aim to reduce the environmental and health impacts of waste and improve Europe's resource efficiency. The long-term goal is to turn Europe into a recycling society, avoiding waste and using unavoidable waste as a resource, wherever possible. Therefore, proper waste management is a key element in ensuring resource efficiency and the sustainable growth of European economies.

The European Directive 2008/98/CE (http://ec.europa.eu/environment/waste/framework/) establishes a five-step waste hierarchy where prevention is the best option, followed by re-use, recycling, energy recovery and, as the last option, landfill disposal, as shown in Fig. 1. Thus, the sustainable strategy for the waste management is to improve waste treatment in the aim to reduce their landfill disposal and minimize the environmental impact.

Energy recovery (WtE by means of biochemical and thermochemical processes) technologies are the only solution, prior to landfill disposal, to handling mixed wastes that cannot be conveniently recycled or re-used from environmental and economic points of view (Brunner and Rechberger, 2015, Fernandez-Gonzalez et al., 2017; Rajaeifar et al., 2017).

In biochemical conversion, MSW is broken down into smaller molecules by microorganisms under aerobic or anaerobic conditions with minimal energy input. This process, much slower than the thermochemical conversion, is only suitable for biodegradable wastes (Shi et al., 2016).

Thanks to the involved high temperatures and the great conversion rates, thermochemical processes can efficiently treat different types of solid waste, in particular unsorted residual waste (i.e. the waste left downstream of separate collection), and can facilitate the control of pollutants that can be more easily reduced and captured (Arena, 2012). Moreover, a waste reduction both in mass (about 70–80%) and in volume (about 80–90%), preserving landfill space (Consonni et al., 2005), is reached. These technologies can be grouped into two main categories: combustion- and gasification based thermal treatments.

Combustion (or incineration), the primary approach for WtE conversion, occurs in the excess of oxygen with respect to the stoichiometric conditions. It is a well established and sustainable technology that results in considerable waste volume reduction with thermal and/or electrical energy generation.

Gasification, that operates in sub-stoichiometric conditions, converts solid wastes into clean gaseous fuel (syngas). In the past two decades, this technology has received increasing attention due to the growing demand for clean fuels and chemical feedstocks, as well as the need for reducing dependency on fossil fuels. With respect to combustion-based processes, gasification has several potential benefits, mainly related to the possibility of obtaining a product syngas suited for use in different applications and to the better control of emissions such as dioxins and furans (the low levels of oxygen present inhibits their formation) (Arena, 2012). Therefore, whereas incineration is focused on the reduction of waste to ash with onsite energy generation, gasification involves the conversion of waste to synthesis gas and inert slag with recovery of energy and valuable metals. Thus, it is a very promising option for implementation of clean poly-generation (electricity,

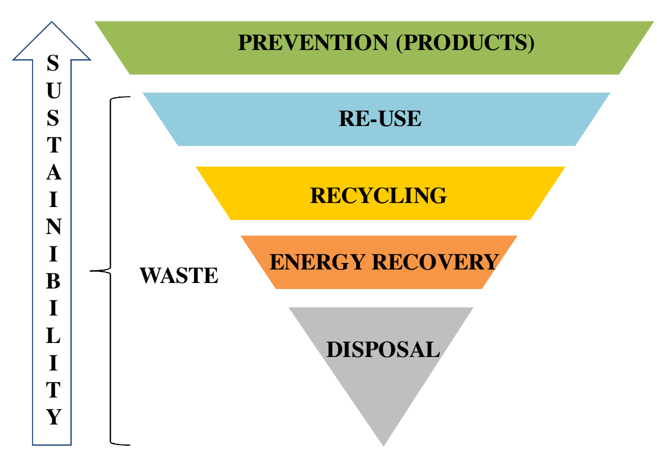

Fig. 1. Waste hierarchy.