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Integrating an oxygen enriched waste to energy plant with cryogenic engines and Air Separation Unit: Technical, economic and environmental analysis

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HIGHLIGHTS

- A techno-economic analysis of integrated system WtE-ASU-DE is provided.
- The environmental assessment is based on pollutant specific emission factors.
- The penalty due to ASU is compensated by LN_2 valorization under opportune conditions.
- DEs allow significant emissions reduction for Transport Refrigeration Unit.

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ABSTRACT

One of the main benefits of using oxygen enriched combustion in Waste-to-Energy plants is the reduction of losses at the stack due to the reduced flue gas production. At the same time, the electricity required by the Air Separation Unit to generate the oxygen, leads to a penalty in energy efficiency that puts at stake its economic feasibility. In order to overcome that criticality, an opportunity is offered by the possibility to exploit one of the main by-products of the Air Separation Units (i.e. liquid nitrogen) by means of a high efficiency open Rankine-cycle expander, namely the Dearman Engine (i.e. cryogenic engine). The proposed research investigates the feasibility of an integrated system - Waste-to-Energy plant, Air Separation Unit and Dearman Engine - in terms of technical, economic and environmental performance indices such as *power output*, *economic savings*, *incremental income* and *pollutant emissions reduction*. The results show that, under opportune conditions (i.e. liquid nitrogen utilization factor and diesel price higher than 83% and 1.08 USD/kg, respectively) the penalty in energy efficiency coming from the integration between the Waste-to-Energy plant and the Air Separation Unit can be compensated, both economically, with a pay-back time inferior to 10 years, and environmentally (saving 23 kton/year of CO_2), by means of the valorisation of the liquid nitrogen through the Dearman Engine.

1. Introduction

The constantly growing worldwide population is leading to a constant increment of waste production [1]. In most developing and developed countries an ongoing challenge is that to collect, recycle, treat and dispose significant quantities of solid waste [1,2]. In this context, Waste-to-Energy (WtE) plants play a crucial role as they convert waste into energy. Among the different technical issues, such as temperature fluctuations of the flue gas [3,4] and high temperature corrosion [5,6], emissions represent one of the main concerns due to the stringent emissions level enforced on WtE plants and to the global trend which focusses on minimizing pollutant emissions [7,8]. A potential solution to reduce emissions consists of adopting a well-established technology in combustion processes: Oxygen Enriched Combustion (OEC). Nowadays, such a technique is mainly adopted in industrial production processes where an oxidant containing higher molar concentration of oxygen than that present in the air, is used to improve the combustion process [9]. The wider adoption of OEC over the last decades is due to several advantages:

– Increase in thermal efficiency: the losses at the stack are reduced because the mass flow rate of the flue gas decreases as the oxygen

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Nomenclature

Acronyms

ASU	Air Separation Unit
CP	Cost per power Unit [MUSD/MW_e]
DE	Dearman Engine
ET	Electric Tariff [USD/kWh_e]
LN_2	Liquid Nitrogen
TRU	Transport Refrigeration Unit

Symbols

β	Specific power consumption [kWh/kg]
C	Cost
ΔI	Economic incremental income [MUSD]
Em	Emissions
ṁ	mass flow rate [kg/h]
N	Number of unit [–]
P	Power [MW_e]
S	Savings

Subscripts

base	baseline
c	cooling
dies	diesel
e	electric
ec	economic
gf	Gate fee
int	integrated
m	mechanical
sav	saved
y	yearly

molar concentration in the combustion air increases: instead of heating up inert nitrogen, more steam is produced in the coupled Rankine cycle of the WtE plant [9].

- Lower emissions: OEC generates lower levels of pollutants (e.g. nitrogen oxide) and of products derived from incomplete combustion (e.g. carbon monoxide, aromatic polycyclic hydrocarbons and chlorinated organic compounds) [10,11].
- Improve temperature stability and heat transfer: increasing the oxygen content allows more stable combustion and higher combustion temperatures that can lead to better heat transfer within the load [9,12].
- Increase productivity: by means of oxygen enrichment of the oxidant gas, the throughput of the plant can be increased for the same fuel input because of higher flame temperature, increased heat transfer to the load and reduced flue gas [13].

Oxygen Enriched Combustion is actually considered one of the most potential technologies for CO_2 capture in power plants. Yin et al. [14] have reviewed pulverized fuels oxy-fuel combustion fundamentals and their recent development with a focus on CFD modeling and systems performance. Hanak et al. [15] have evaluated the techno-economic performance of cryogenic O_2 storage implemented in an oxy-combustion coal-fired power plant as a means of energy storage. The proposed system compensates the average daily efficiency penalty of the system with higher daily profit by 3.8–4.1% only if the carbon tax is higher than 29.1–29.2 €/tCO2. Xiang et al. [16] have proposed an integrated system of Natural gas combined cycle and oxy-fuel combustion finding a significant increase of the power generation efficiency. Pettinau et al. [17] have compared three different power generation technologies for CO2-free power generation from coal finding that, although not enough mature for commercial-scale applications, oxy-coal combustion has a relevant future potential due to its relatively low levelized cost of electricity (62.8 €/MWh).

From an industrial perspective, oxygen enriched combustion is a well-established practice in the glass [18], steel, iron [19,20] and cement industries [21]; however this is not the case in WtE plants in which the economic penalties associated with the production of oxygen used to enrich the combustion process, overcome the operative and environmental benefits [22]. Even though oxygen enriched combustion leads to higher thermal efficiencies (and hence to higher electricity generation) of the WtE plants, the electricity required by the Air Separation Unit (ASU) to produce oxygen is more than the extra energy produced by the WtE plant, thus resulting in an overall reduction in power supply capacity [23,24]. According to Mathieu [25], an oxy-fuel combustion process applied to power generation systems leads to a penalty in energy efficiency equal to 10–14%. The economic penalty introduced by oxygen enriched combustion in WtE plants has been evaluated by Verdone et al. [26] who computed a net disadvantage in the range of 0.016–0.035 €/kg_{waste}, an increase in specific treatment cost of waste mainly caused by the oxygen production cost. A possible way to enhance the economic feasibility of an integrated plant composed by a WtE plant and an ASU is offered by the opportunity to use the by-products coming from the ASU (mainly nitrogen streams in gaseous or liquid form) [27]. A promising technical solution is represented by a high efficiency open Rankine-cycle expander, the Dearman Engine [28], which uses liquid air (or liquid nitrogen, LN_2) as main energy vector. The introduction of cryogenic engines running on liquid air could produce substantial economic and environmental benefits to the integrated plant WtE-ASU since it allows monetizing the by-products from the ASU. Indeed the Dearman Engine (DE) could be used in a number of configurations [28]: as the 'prime mover' or principal engine of a zero emissions vehicle; combined with an internal combustion engine (ICE) to form a 'heat hybrid' engine that converts waste heat from the ICE; or as a 'power and cooling' refrigeration unit (TRU).

This works tries to propose an innovative integrated system that is based on the integration of Waste-to-Energy plant with Air Separation Unit and cryogenic engines. The comparative analysis aims to highlight whether and how much the integrated systems are technically, economically and environmentally superior over the baseline case study. Two configurations for two different commercial sectors have been analyzed: (1) a cold and power refrigeration unit (DE-TRU) for the transport of frozen goods and (2) a waste heat recovery/air conditioning unit employed in the public transport (DE-Bus). The analysis has been carried out to assess the technical, economic and environmental feasibility of the two selected configurations (DE-TRU & DE-Bus) coupled with the integrated plant (WtE-ASU). Real data provided by Dearman Engine have been implemented in our model in order to further enhance the real applicability of the results.

In Section 2 the baseline case study, the integrated system[1] (WtE-ASU-DE) and the main key performance indices will be introduced and explained. In Section 3, the results from the energy, economic and environmental analysis will be shown and finally the main conclusions will be drawn.

2. Methodology and approach

2.1. The baseline case study: Waste-to-Energy plant and diesel engines

In order to compare and assess the possible benefits introduced with the integrated system, two different baseline case study have been considered as described below.

[1] In the paper, the following terminology will be used: 'integrated plant' for the WtE-ASU and 'integrated system' for the WtE-ASU-DE.