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Technical and economic optimization of subcritical, wet expansion and transcritical Organic Rankine Cycle (ORC) systems coupled with a biogas power plant

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ABSTRACT

Generally, > 40% of the useful energy (cooling engine and exhaust gases) are wasted by a biogas power plant through the cooling radiator and the exhaust gases. An efficient way to convert this waste heat into work and eventually electricity is the use of an organic Rankine cycle (ORC) power system. Over the last few years, different architectures have been widely investigated (subcritical, wet expansion and trans-critical). Despite the promising performances, realistic economic and technical constraints, also related to the application, are required for a meaningful comparison between ORC technologies and architectures. Starting from the limited literature available, the aim of the present paper is to provide a methodology to compare sub-critical, trans-critical and wet expansion cycles and different types of expanders (both volumetric and turbomachinery) from both technical and economic point of view, which represent one of the main novel aspects of the present work. In particular, the paper focuses on the thermo-economic optimization of an ORC waste heat recovery unit for a 500 kWe biogas power plant located in a detailed regional market, which was not investigated yet. By means of a genetic algorithm, the adopted methodology optimizes a given economic criteria (Pay-Back Period, Net Present Value, Profitability Index and Internal Rate of Return) while respecting technical constraints (expander limitations) and thermodynamic constraints (positive pinch points in heat exchangers, etc.).

The results show that optimal ORC solutions with a potential of energy savings up to 600 MWh a year and with a pay-back period lower than 3 years are achievable in the regional market analysed.

1. Introduction

Nowadays, the increase of energy consumption has led to concerns due to the strong environmental impact in terms of global warming and pollution. The EU emanated several directives aimed to reduce the environmental impact of our society by fostering the development of advanced and effective energy efficiency policies [1].

In this context, recovering and reusing the low-grade heat wasted by industrial processes represents an effective way to increase the overall performance of a process and, consequently to reduce the primary energy consumption and the carbon footprint. Generally, the so-called Waste Heat Recovery (WHR) can be applied to any process where a heat source with a temperature higher than 80–100 °C occurs [2].

Among others, the Organic Rankine Cycle (ORC) technology is a promising technique to produce electricity by exploiting this low-grade heat. Like a conventional steam power plant, an ORC cycle is a Rankine cycle in which an organic substance (usually synthetic refrigerants or hydrocarbons) is adopted as working fluid. A strong interest on this technology has been raised over the last few years due to the wide range of possible applications. As for instance, Campana et al. [3] estimated an installation potential of 2705 MW_e in Europe, which would lead to about 21.6 TWh_e of electricity production with a corresponding reduction of greenhouse gas emissions (GHG) of about 8.1 million. Consequently, a lot of efforts have been put by researchers and engineers to investigate deeply the performance and benefits of this technology [4–8].

Generally, the investment cost of an ORC system is in the 1200–9500 USD/kWe range, but, as highlighted by [9–10], the specific application, the type of heat sources available and the ORC architecture strongly influence the actual values. Moreover, the specific market context and the investment policy adopted assume a relevant role when a potential investment is assessed [11]. Notwithstanding, a lack of

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Nomenclature

A	area [m^2]
AD	anaerobic digester
B	capacity parameter [W] or [m^2]
Bo	boiling number [–]
C	cost [€]
C_p	isobaric specific heat [J/kg/K]
CHP	combined heat and power
CF	cash flow [€]
D	correlation coefficient [–]
D_h	hydraulic diameter [m]
E	exergy [kJ/kg]
f	friction factor
F	factor [–]
h	convective heat transfer coefficient [kW/(m^2K)]
H	enthalpy [kJ/(kg)]
i	index
Inv	investments [€]
IRR	interest rate of return [–]
j	index
k	thermal conductivity [W/mK]
K	correlation coefficient [–]
L	characteristic length [m]
LCOE	levelized cost of electricity
LHV	low heating value [J/kg]
$\dot{m}$	mass flow rate [kg/s]
NI	Northern Ireland
NPV	net present value [€]
Nu	Nusselt number
ORC	organic Rankine cycle
p	pressure [bar]
P	pitch [m]
PBP	pay back period [–]
PEF	primary energy factor [–]
PI	profitability index [–]
Pr	Prandtl [–]
$\dot{Q}$	heat transfer rate [W]
r	discount rate [–]
R	thermal resistance [K/W]
Re	Reynolds [–]
SP	size parameter [–]
T	temperature [°C]
U	heat transfer coefficient [W/(m^2·K)]
$\dot{V}$	volumetric flow rate [m^3/s]
VC	volume coefficient [m^3/J]
VR	volume ratio [–]
W	energy [kWh]
WHR	waste heat recovery
$\dot{W}$	power [W]
x	state of the fluid at the exhaust of the evaporator
y	time [year]

Greek

β	Chevron angle [°]
Δ	difference
ε	effectiveness [–]
η	efficiency [–]
μ	dynamic viscosity [kg/m/s]

Indices

aux	auxiliary
b	bulk
el	electrical
eV	evaporator
ex	exhaust
exp	expander
gas	gas
is	isentropic
LMTD	log mean temperature difference
net	net
pp	pump
sf	secondary fluid
su	supply
w	wall
wf	working fluid

information is still present from an economic point of view taking into characteristics of the market in which the system is located in, and it represents a paramount aspect for the diffusion of this technology.

One of the most promising applications for ORC systems is represented by biogas power plants [12–15]. Generally, biogas is produced locally by the anaerobic digestion (AD) of organic substrates coming from organic waste streams, e.g. biological feedstocks from agricultural sectors [13], and it can be used as renewable fuel for transports (after a cleaning treatment) or to produce electricity by means of CHP engines (biogas power plants, or AD-CHP) [14]. As for other biofuels, biogas is an important priority of the European energy policy since it is a cheap and CO_2-neutral source of renewable energy, which offers the possibility of treating and recycling a wide range of agricultural residues and products. Therefore, an impressive development of AD-CHP plants occurred over the last few years and > 17,000 plants were operational in Europe in 2014 with a total installed capacity of 8.293 GW_{el} [15]. Generally, only 40% of the biogas energy content is transformed into electricity [16], while about 25% is used for the internal parasitic load and for heating the digester to keep the biological temperature required to allow the chemical processes. The remaining part is generally released into the atmosphere in form of heat by the exhaust gas (high temperature, > 350 °C) and by the radiators (low temperature, < 120 °C). An organic Rankine cycle system might be used to exploit part of this heat to produce further electricity, increasing the overall performance of the AD-CHP system.

Despite the amount of work done to analyse the ORC systems, including the direct use of biogas as thermal source of the ORC system [13,16,17–20], the WHR application for biogas plant has not been fully investigated yet. As for instance, Yangli et al. [14] performed a technical investigation of subcritical and supercritical ORC systems which exploit the heat rejected from a biogas CHP engine, obtaining ORC thermal efficiencies of 15.51% and 15.93% for subcritical and supercritical cycles respectively. The authors concluded their work highlighting that a thermo-economic analysis should be carried out to detect the configuration which guarantees the best repayment period. At this regard, Sung et al. [15] performed a thermo-economic analysis of a biogas micro-turbine system coupled with a subcritical ORC cycle with a turbine as expander. The analysis, limited to one working fluid (n-Pentane), is mainly focused on partial load operating conditions of the biogas micro-turbine. Notwithstanding, the authors demonstrated that the introduction of a bottoming ORC provides a net gain from an economic point of view, despite the analysis was limited to only one economic parameter (Net Present Value, see Section 3.3).

Therefore, a lack of thermo-economic analyses on WHR-ORC for biogas power plant applications is still present. In this context, the aim of the present paper is to extend the analysis to a wider range of potential ORC configurations (namely subcritical, trans-critical and wet expansion cycles [8,21–22]) and working fluids. Different AD-ORC