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Case study of an organic Rankine cycle applied for excess heat recovery: Technical, economic and policy matters

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ABSTRACT

Many industrial processes inevitably produce excess heat as by-product. Recovering this heat is a matter of waste management and provides opportunities to improve the energy use efficiency. The excess heat can be used for heating purposes (e.g., in processes, or delivered to district heating systems or buildings) or to generate electricity. An increasingly applied technology for industrial excess heat recovery is the organic Rankine cycle (ORC), suitable to recover low-grade heat from 90 °C onwards. Although ORCs are studied intensively, few studies have examined the economics of commissioned ORC systems. This paper investigates a 375 kW_{gross} ORC system employed for flue gas heat recovery from an industrial kiln in Flanders, Belgium. The purpose of the study is twofold: providing insight into a practical ORC case; and evaluating the financial feasibility while taking the specific policy circumstances into account. The financial appraisal takes account of the specific technical setup, the diverse costs of the system, the external economic parameters, and the policy circumstances in Europe, Belgium and Flanders. A sensitivity analysis illustrates the influence of each parameter on the results. The analysis demonstrates the dominance of the investment costs (4217 $€_{2013}/kW_{gross}$) in the expenses. Under the valid conditions the investment has a positive financial return, but the financial support from the government is indispensable. Finally, the sensitivity analysis reveals the importance of attaining sufficient load hours and the influence of electricity prices on the financial feasibility of ORC projects. The results suggest that ORC systems are suitable for industrial excess heat electricity production under certain conditions, but financial support remains necessary. Reducing the investment costs of the ORC itself could alleviate these conditions.

1. Introduction

Our economies have a long history in large-scale exploitation of fossil fuel and nuclear sources for power production. Confidence in the infinite character of the sources caused copious, supply-induced electricity systems. Today, the traditional fossil-nuclear oligopoly is challenged by resource- and climate-related and geopolitical issues. The latest Intergovernmental Panel on Climate Change (IPCC) report confirms the continuous increase of anthropogenic greenhouse gas emissions despite numerous mitigation policies [1]. Fossil fuel combustion and industrial processes make up the largest contributors (±78%) [1]. Addressing CO_2-emissions requires decreasing the carbon intensity of electricity supply and demand reduction via efficiency improvements and behavioural change [1]. Supply side alternatives exist in the form of renewable sources. Reducing the intensity of our energy demand includes increasing the efficiency of this use. The worldwide industry sector is responsible for 29% of final energy use (in 2014), and emitted approximately 13 Gt CO_2 in 2010 [1,2]. It is estimated that a 25% reduction in energy intensity of the industry sector could be achieved directly by wide-scale upgrading, replacement and deployment of best available technologies [1]. However, actual implementation of energy efficiency is hindered mainly by initial investment costs and lack of information [1].

This paper focusses on the industry's potential to improve the efficiency of its energy use by means of excess heat recuperation, more specifically with organic Rankine cycle (ORC) technology. The heat dissipated by a process may be inevitable but could be utilized as input for heating, cooling or power systems. ORC technology finds increased application in renewable electricity production, but also for industrial heat recovery. In recent years, many investigators have developed and analysed innovative ORC designs. As discussed in previous work, the ORC research field is dominated by technical studies [3]. In practice however, the feasibility and desirability of an ORC system is not merely determined

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Nomenclature

C_0	capital investment [€]	$C_{F,t}$	fuel costs in year t [€]
C_S	investment support [€]	r	discount rate [%]
C_t	net cash flows in year t [€]	S	salvage value [€]
D_t	depreciation in year t [€]	T	tax rate [%]
E_t	electricity production at time t [kW h]	t	year [–]
n	economic lifetime of the project [years]	TD_t	tax deduction [%]
$O\&M_t$	operation and maintenance costs in year t [€]		

by its technical specifications. The economic appeal of ORC technology remains opaque with only few publications that discuss the costs of actual ORC systems, the majority discussing the economics based on estimated rather than real costs [3]. For instance, Amini et al. [4] investigate a transcritical ORC for heat recovery from a combined-cycle power plant in Iran and estimate the specific investment costs (SIC) for the project at 2625 $/kW. Kwak et al. [5] investigate several scenarios for integration of an ORC system in an industrial reference site and estimate the additional investment costs between 10.7 and 16 million $ depending on the scenario. Lecompte et al. [6] evaluate the SIC of a simulated heat recovery ORC and point at the difference between specific investment costs considering the system's installed capacity and its actual power output due to part load conditions. Lecompte et al. [7] perform a multi-objective optimization to compare the subcritical and transcritical ORC for heat recovery in terms of SIC and net power output. Imran et al. [8] simulate and optimize a basic (3556 $/kW), single (3749 $/kW) and double stage (4057 $/kW) regenerative heat recovery ORC for maximum thermal efficiency and minimum SIC. Many other studies investigating ORCs for heat recovery focus on diesel engine heat recovery for marine or offshore applications. For instance, Yang et al. [9] investigate the thermodynamic and economic performance of an ORC system for heat recovery from a diesel engine, using different working fluids. The best performance was measured for an ORC with R245fa as working fluid, an 11.55 kW net output and a capital cost of 533 k$. Similarly, Yang and Yeh [10] compare different working fluids in marine diesel settings and obtain the best results, in terms of net power output over total system costs, for a system using R1234yf with a net power output of 320 kW and a cost of 1203 k$. In a follow-up work, Yang [11] analyses the performance of compact transcritical ORCs for marine applications. The economic performance is best for a system which recovers the thermal energy from all three sources (the scavenge air cooling water, the cylinder cooling water and the exhaust gas) (4768 k$ for 3049 kW). Finally, Pierobon et al. [12] investigate heat recuperation from an offshore platform gas turbine in Kristiansund, The North Sea. The optimal system in a first case with a 30 m^3 volume limit for the ORC costs 13 million $ for 6 MW net power output. A second case permits more than 100 m^3 volume for the ORC, which yielded an optimum for 6.43 MW net power output (at 15 M$). Real ORC costs are published, for instance, for the first biomass ORC power plant installed in the European Union in Admont, Austria. The 400 kW ORC combined heat and power was installed in 1999 for an investment cost of about 3.2 million euros [13]. In 2009, the same constructor published prices for biomass fuelled ORC systems in the range of 4500 €/kW for an 1803 kW system to 10,200 €/kW for a 345 kW system [14]. Leslie et al. [15] discuss a 5.5 MW heat recovery ORC system, recovering thermal energy from a gas turbine driving a natural gas pipeline compressor, with a capital cost of about 2500 $/kW. More recently, Tumen Ozdil et al. [16] discussed a 260.4 kW heat recovery ORC plant installed in Adana, Turkey with an investment cost of $ 500,000, but the commissioning date of the system is unfortunately unknown [29]. Toffolo et al. [17] perform a bottom-up ORC cost estimation and compare the results with the costs from an actual case. The geothermal reference system has an installed capacity of 33.6 MW for a total capital investment of 132 million euros (2009), including well drilling and indirect costs.

Hence, little research has described or analysed the economics of real ORC systems. When technical feasibility is assured, the adoption of a technology depends to a large extent on the financial feasibility of the investment. A better understanding of the parameters influencing the economics of ORC investments is paramount for assessing the technology's economic potential, rather than its technical potential. This paper aims to contribute by reporting the case of an industrial heat recovery ORC system installed in the Flanders Region, Belgium. The paper is organized as follows. Section 2 discusses the definition of 'waste heat' and outlines the working principle of ORC technology for heat recovery. This paper avoids utilizing the terminology 'waste heat', but refers to 'excess heat' instead to evade confusion with other types of waste. Section 3 discusses the technical setup of the ORC system, its economic characteristics and the relevant public policy for the investment (see also Lemmens [18]). The central issue in this work is the discussion of the financial project appraisal (Section 4) and the assessment of public policy influence and the sensitivity of the results for changes in project parameters (Section 5).

2. Excess heat recovery with an organic Rankine cycle system

The ORC can be used to generate power from lower temperature heat sources. The focus in this work lies on the utilization of industrial excess heat. This section starts by defining the concept 'excess heat', by summarizing current insights in the potential of industrial excess heat and by briefly introducing the working principle of an ORC.

2.1. Excess heat recovery, energy efficiency and excess heat availability

Industrial excess heat recovery: heat streams that would otherwise be dissipated could be recovered and employed for heating purposes or electricity generation. The idea is conceptually simple but requires an a priori definition of excess heat itself. The opposite, 'useful heat', is defined by the European Union as "heat produced in a cogeneration process to satisfy economically justifiable demand for heating or cooling" [19]. Bendig et al. [20] identify several levels of detail for defining 'waste heat':

- "*Waste heat is heat dissipated to the environment*". This definition follows the first law of thermodynamics and has the energy balance as a basis (the higher the input, the higher the output). Users of this definition often disregard the temperature of the heat stream and its potential use and reuse.
- "*Low grade waste heat is heat that is not viable for heat recovery within the process*". This definition includes the notion of usefulness, thereby pointing at the possibility of heat recycling. Process efficiency optimization then occurs in a hierarchical