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Key performance indicators for integrated natural gas pressure reduction stations with energy recovery

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ABSTRACT

The pressure drop between the gas transportation grid and local networks can be exploited to generate electricity by means of a turbo expander. However, a lack of performance indicators leads to incomprehension and underestimation of the actual benefits in terms of energy savings and carbon emission reductions, thus limiting the diffusion of such smart, energy-saving technology. For this reason, in this study, key performance indicators are proposed for natural gas pressure regulation stations with energy recovery. The waste energy recovery index is introduced by considering the possibility of system thermal integration and a reference theoretical sideways process, where a Joule-Thompson expansion occurs. Furthermore, the reduction of greenhouse gas emissions is evaluated through the carbon emission recovery index that quantifies the environmental benefits of the energy saving action. Different key performance indicator values have been calculated by means of custom prediction models based on system characteristics. Finally, in order to assess the accuracy of such models, a parallel simulation is conducted using *UniSim® Design Suite* software. Here, the two system configurations are implemented: one related to the case study and one related to the reference sideways process. The results show that the model successfully predicts the heat needs of pressure reduction stations and, for a typical system configuration, characterised by an expansion ratio of 4.8, a maximum waste energy recovery of about 69% could be achieved when the system is operating at nominal conditions. Proposed KPIs turned out to be a helpful tool to manage design development and system operations. Moreover, the simplicity of the performance indexes makes them easy to implement in software for process control and simple to interpret for system operators.

1. Introduction

In recent years the use of Natural Gas (NG) has been continuously rising for several applications, including heating, electricity production and the industrial sector [1]. In 2016 NG covered about 21% of world energy demand [2] and the trend is still strongly positive, so the International Energy Agency forecasted a 50% growth of NG demand by 2040 [3]. In parallel, NG transportation and distribution networks are constantly expanding in order to provide a reliable and diffused delivery service. On a global scale, thanks to rising penetration in Asia, namely in China and India, and Africa, worldwide demand has grown by more than 30% in the last 15 years [4], with a consequent rapid development of gas infrastructures. In Europe the NG network system has been continuously increasing and further extensions are expected towards Russia and Azerbaijan and through liquefied natural gas infrastructures [5].

This scenario has led researchers to focus on energy recovery opportunities from the NG transportation and distribution grids. Kostowski [6] analysed this possibility through a theoretical approach, while Andrei et al. [7] developed an experimental study, both concluding with a positive assessment. Generally speaking, NG pressure must be reduced before being delivered to distribution nodes. For this purpose, in conventional NG Pressure Reduction Stations (PRSs) expansion occurs through a dissipative process using throttling valves. In most cases, depending on the inlet and outlet conditions, NG must be pre-heated in order to avoid methane-hydrate formation [8]. When aiming to recover energy from NG expansion, the key idea is to exploit the pressure drop between the transportation pipeline and the local distribution network to generate electricity, usually by replacing the throttling valves with a turbo-expander (TE) [9]. Because of the relevant pressure difference and mass flow rate in the PRSs that connect high and low-pressure branches of NG grids, the amount of energy recovered and converted can actually be considerable. Neseli et al. [10] estimated 4.11 GW h/year of energy recovered by the TE in their case study. In this study, the system involves conventional boilers working with temperatures of 70–90 °C with an average annual fuel

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Nomenclature

AE	instantaneous avoided carbon emissions (kg/h)
$\overline{AE}$	average avoided carbon emissions (kg)
CER	instantaneous carbon emission recovery (%)
$\overline{CER}$	average carbon emission recovery (%)
c_p	thermal grid energy vector's heat specific value (kJ/kg K)
E_{rel}	recovery process power production (kW)
e_{rel}	relative process carbon emission (kW)
E_{WER}	recovery process power production (kW)
e_{WER}	recovery process carbon emissions (kg/h)
LHV	Lower Heating Value
$\dot{m}_{fuel_{WER}}$	fuel mass flow for recovery process (kg/s)
$\dot{m}_{grid}$	thermal grid water energy vector flow rate (kg/s)
$\dot{m}_{TE}$	turbo expander natural gas flow rate (kg/s)
$\dot{m}_{tot}$	total natural gas flow rate (kg/s)
P_{TE}	turbo expander power output (kW)
PQ	power/heat ratio
$\overline{PQ}$	average power/heat ratio
PQ_{eff}	effective power/heat ratio
$\overline{PQ}_{eff}$	average effective power/heat ratio
Q_{TE}	instantaneous turbo expander preheating load (kW)
$Q_{rel}^{preheating}$	instantaneous relative preheating load (kW)
Q_{th}^{grid}	instantaneous thermal grid heat load (kW)
$Q_{tot}^{preheating}$	instantaneous total preheating need (kW)
Q_{tot}	instantaneous heat load (kW)
R	recovery factor
$\overline{R}$	average recovery factor
t_0	time lower bound (s)
t	time upper bound (s)
T_{in}	thermal grid inlet temperature (K)
T_{out}	thermal grid outlet temperature (K)
WER	Waste Energy Recovery index (%)

Abbreviations

CHP	Combined Heat and Power
DHN	District Heating Network
NG	Natural Gas
PRS	Pressure Reduction Station
RES	Renewable Energy Sources
TE	Turbo Expander
TV	Throttling Valve

Greek letters

β	expansion ratio
γ	national electric grid emission factor (kg_{CO2}/kW h)
δ	thermal unit carbon emission factor (kg_{CO2}/kW h)
$\overline{\eta}_{el\,grid}$	national electricity production efficiency
$\overline{\eta}_{th}$	thermal unit, average thermal efficiency
η_{th}	thermal unit, thermal efficiency

consumption of about 0.32% of the total amount of NG passing from the PRS. Besides, Borelli et al. [11] calculated an electricity generation of 2.9 GW h/year for a total heat consumption of about 3.1 GW h/year.

However, when a TE is employed to recover energy from PRSs, the NG preheating requires more thermal energy to maintain the minimum admissible NG outlet temperature. This is because the work generated by the TE is partly due to the thermodynamic conversion of the heat supplied to the NG flow during the preheating process, so more heat is needed than for conventional throttling valves. This condition opens the issue of optimising energy recovery and of assessing its effectiveness. In order to improve the conversion efficiency, Arabkoohsar et al. [12] studied the possibility of employing solar energy for gas preheating, while Farzaneh-Gord et al. [13] investigated geothermal integration in PRSs with TE. Even the use of a molten carbonate fuel cell to preheat the gas before it flows through the TE was studied by Howard et al. [14], with the objective of investigating the factors affecting the performance of such a system. Likewise, PRS thermal integration with a nearby combined conversion process was analysed by Borelli et al. [11] and Kostowski and Usòn [15]. An innovative system for NG expansion was analysed by Farzaneh-Gord in [16]. Here the optimisation of a reciprocating expansion engine for energy recovery was studied. In [17], the possibility of reducing the system operating temperature was investigated. As described by the authors, this is a key aspect for low temperature heat source system integration and waste heat utilisation. Sanaye and Nasab in [18], defined a relative quick method to find the required number of gas engines/boilers, and determine their nominal power/heating capacity in PRSs. In [19] Farzaneh-Gord et al. conducted an energy, economic and carbon emission assessment for a ground coupled heat pump for a PRS. Moreover, the use of cogeneration units in PRSs was generously investigated in [20], where a technical criterion for assessing the economic feasibility of such units was developed. Recently, Arabkoohsar et al. [21] presented an energy and economic analysis of cogeneration-based-stations based on eight different stations. Here a technical criterion was defined to classify those stations suitable for hosting cogeneration technologies. Finally, a combination of a solar assisted absorption chiller and a PRS unit was analysed. Here, an annual cooling production contribution of 27% can be provided by the integration with a PRS.

So, if a certain expertise has been developed in operatively increasing the efficiency of PRS recovery systems through the integration with renewable energy sources or Combined Heat and Power (CHP), the topic of assessment of the global energy efficiency of the process has not yet been thoroughly explored. It is obvious that the characteristics of the heat source chosen for NG preheating affect the efficiency of the recovery process, and that the above mentioned thermal integrations enhance its performance. At the same time, it is definitely more complicated to quantitatively assess how the hybrid conversion process and energy recovery are influenced by the several thermodynamic parameters involved, starting with the features of the preheating energy source. In some papers, Kostowski addressed definition of figures of merit in order to assess the efficiency of recovery systems and to compare the performance of alternative configurations. In [15] energy and exergy analysis of the PRS was developed and indicators were proposed to evaluate the corresponding CO_2 emissions. Several different performance indicators were defined, calculated and discussed in [22], where both energy and exergy efficiency parameters were presented in order to compare different possible set-ups. Performance Ratio, Incremental Performance Ratio and Local Differential Efficiency refer to energy balances, while several formulations of exergy efficiency ratio are based on the 2nd Law of Thermodynamics. A comparative analysis of electricity generation in PRSs based on thermo-ecological cost was proposed in [9], aiming at a thermodynamic evaluation of energy resource management. The assessment method considered both the interrelation of irreversibility for the system analysed and its influence related to depletion of non-renewable resources. More recently, Lo Cascio et al. [23] focused on control optimisation of integrated PRSs. Depending on the system configuration, a model was proposed enabling an assessment based on how the NG preheating process is implemented for reference time intervals. That assessment was mainly achieved by weighting the electricity generated by the TE and linking it to customised energy remuneration tariffs.

However, there is still a vagueness in the analysis of Waste Energy Recovery (WER) in PRSs. On the one hand, WER efficacy is intimately related to system design, NG flow rate, pressure drop, control technique