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Performance assessment of a novel natural gas pressure reduction station equipped with parabolic trough solar collectors

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ABSTRACT

World's energy picture is still framed in a context characterised by extensive use of the natural gas. Luckily there are significant opportunities for increasing energy efficiency and fostering energy recovery in natural gas infrastructures. In particular integration with renewable energies is an asset to be exploited. This paper presents a novel configuration of the so-called natural gas pressure reduction stations equipped with sun-tracking parabolic trough solar collectors. In addition, the system is coupled with thermal energy storage. The energy and environmental performance of this new configuration is investigated with the support of a dynamic model implemented in *Matlab-Simulink*®. Energy saving has been calculated for three European cities, namely Genoa, Naples, and Amsterdam, characterised by different latitudes and hence solar irradiations. The results revealed that, despite the technical and physical constraints, it is possible to achieve carbon-free operations in summer periods for southern locations. The proposed system configuration has shown to be a strategic retrofit intervention to pursue reducing carbon emissions linked to the gas distribution operations.

1. Introduction

As oil and coal fall back and renewables ramp up strongly, natural gas (NG) becomes the largest single fuel in the global mix [1]. The NG can help the transition to a sustainable and clean energy scenario. A smart integration between NG transportation grid and renewable energy sources (RES) is one of the strategic actions to pursue. NG is transported through several states by a tentacular infrastructure till distribution nodes [2]. At this level, the NG pre-distribution treatments are conducted in the so-called pressure reduction station (PRS) and these include gas metering, filtering, preheating and pressure reduction. The gas preheating is essential to avoid the formation of methane hydrates that could result in pipe corrosion or component damage. For this purpose, the preheating temperature ranges between 55 °C and 85 °C depending on the system characteristics, NG composition and pressure drop [3,4]. More precisely, the high-pressure NG could be expanded using Joule-Thomson (JT) valves or turbo-expanders (TE) which enable energy harvesting. However, this last process, for fixed NG flow rate, requires higher thermal power at higher operating temperature than the JT as commonly known [5]. Conventional fossil-fuel based technologies can provide the necessary energy to accomplish the process. Therefore, the possibilities to achieve better performing PRS operations through system thermal integration and optimisation were also investigated in Refs. [6,7]. Kostowski et al. [8] investigated the integration of internal combustion (IC) engine with an organic Rankine cycle. The feasibility of possible alternative system configurations was investigated in studies [9,10], in which the integration with geothermal heat pumps and fuel cells was studied respectively. However, these configurations might result in high investment, and thus, the use of combined heat and power (CHP) technologies could represent an alternative. For this purpose, in studies [11–14], the CHP issue was investigated. In general, the use of CHPs in PRS might be economically sustainable for most cases. However, efficient primary energy conversion operations are required to justify the investment. Last but not the least, the integration of PRS with RES was analysed by Farzaneh-Gord in Ref. [15], where a case study located in Birjand city was presented. A non-controllable solar flat-plate collector array integrated with a fossil-fuel-based heater was considered to heat-up the NG. This case study was further enhanced, as reported in

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Nomenclature

A_a	Aperture area of the collector (m^2)
A_{am}	Collector, heat loss area from the steel tube to the ambient (m^2)
A_f	Collector, heat transfer area from the steel tube to the HTF (m^2)
C_f	Collector, high temperature fluid heat capacity (J/K)
c_f	Collector, high temperature fluid specific heat capacity (J/kgK)
C_b	Collector, steel tube heat capacity (J/K)
C_{min}	Heat exchanger, minimum fluid heat capacity (J/kgK)
C_{steel}	Boiler, stainless steel specific heat capacity (J/kgK)
C_w	Boiler, water specific heat capacity (J/kgK)
c_p	Thermal storage, water specific heat capacity (J/kgK)
C_r	Heat exchanger, heat capacity ratio
D_{Plug}	Joule-Thomson valve, plug diameter (m)
G_{dni}	Collector, direct normal solar irradiance (W/m^2K)
K_G	Joule-Thomson valve, flow coefficient (kg/sPa)
$K(\theta)$	Collector, incident angle factor
m	Thermal storage, water mass (kg)
$\dot{m}$	Collector, high temperature fluid mass flow rate (kg/s)
$\dot{m}_{i,p}$	Users, plenum natural gas inlet mass flow rate (kg/s)
$\dot{m}_i$	Header, ith water stream mass flow rate (kg/s)
$\dot{m}_{i,p+1}$	Users, plenum natural gas outlet mass flow rate (kg/s)
$\dot{m}_w$	Boiler, water mass flow rate (kg/s)
$\dot{m}_{TE}$	Turbo-expander, natural gas flow rate (kg/s)
$\dot{m}_{tot}$	User, natural gas total demand (kg/s)
M_{steel}	Boiler, steel mass (kg)
M_w	Boiler, water mass (kg)
k	Turbo-expander, natural gas heat specific ratio
$\dot{L}_s$	Thermal storage, user thermal load (W)
p_i	Users, plenum inlet pressure (Pa)
P_{in}	Joule-Thomson valve, natural gas inlet pressure (Pa)
P_{out}	Joule-Thomson valve, natural gas outlet pressure (Pa)
$P_{out,TE}$	Turbo-expander, outlet pressure (Pa)
P^*	Joule-Thomson valve, natural gas pressure at reference conditions (Pa)
q	Joule-Thomson valve, natural gas flow rate (kg/s)
$\dot{Q}_{aux}$	Thermal storage, auxiliary heat gain (W)
$\dot{Q}_{sol}$	Thermal storage, solar heat gain (W)
$b\dot{Q}_b$	Boiler, thermal power output (W)
$\dot{Q}$	Heat exchanger, power exchanged (W)
R_{ba}	Collector, overall heat transfer resistance from steel tube to the ambient (K/W)
R_{bf}	Collector, overall heat transfer resistance from steel tube to high temperature fluid (K/W)
R	Gas constant (J/kgK)
s	Joulet-Thomson valve, plug area (m^2)
S	Collector, effective incident solar irradiance (W/m^2K)
T_a	Thermal storage, ambient temperature (K)
$T_{c,i}$	Heat exchanger, cold fluid inlet temperature (K)
T_{fi}	Collector, high temperature fluid inlet temperature (K)
T_{fo}	Collector, high temperature fluid outlet temperature (K)
$T_{h,i}$	Heat exchanger, hot fluid inlet temperature (K)
T_{in}	Boiler, water inlet temperature (K)
T_{out}	Boiler, water outlet temperature (K)
T_{out}^{header}	Header, water outlet temperature (K)
$T_{out,TE}$	Turbo-expander, natural gas outlet temperature (K)
T_i	Header, ith water stream temperature (K)
$T_{i,p}$	Users, plenum inlet temperature (K)
$T_{in,TE}$	Turbo-expander, natural gas inlet temperature (K)
T_s	Thermal storage, water temperature (K)
T^*	Joule-Thomson valve, natural gas temperature at reference conditions (K)
T_1	Joule-Thomson valve, natural gas inlet temperature (K)
y	Joule-Thomson valve, actuator position (m)
W_{TE}	Turbo-expander, mechanical power output (W)
V_p	Users, plenum volume (m^3)
U_{ba}	Collector, overall heat transfer coefficient from steel tube to ambient (W/m^2K)
U_{bf}	Collector, overall heat transfer coefficient from steel tube to high temperature fluid (W/m^2K)

Greek letters

η_e	Turbo expander isoentropic expansion efficiency
ε	Heat exchanger, effectiveness
ρ	Collector, mirror reflectance
$(\gamma\tau\alpha)_n$	Collector, effective transmittance–absorptance-intercept factor product at normal incidence
ρ^*	Joule-Thomson valve, natural gas density at reference conditions (kg/m^3)
τ	Time (s)

Abbreviations

BO	Boiler
CHP	Combined heat and power
HDR	Header
HE	Heat exchanger
HTF	High temperature fluid
JT	Joule-Thomson
NG	Natural gas
NTU	Number of transfer units
P	Pump
PRS	Pressure reduction station
PTSC	Parabolic trough solar collector
RES	Renewable energy source
SCM	Standard cubic meter
TE	Turbo-expander
TS	Thermal storage
VIGV	Variable inlet guide vanes

Ref. [16]. In fact, the same system configuration was analysed by including automatic control, and the results were compared with the case where no TE was implemented. The local solar irradiation has been estimated by considering solar engineering formulation in both cases [17]. These studies, conducted in Iran, where solar irradiance conditions are favourable, revealed that the integration with solar energy is a strategic action for carbon emissions reduction in PRS operations.

Thus, solar-boosted PRSs might be an excellent option for smart transition to a sustainable and clean energy scenario for other contexts as well. Considering that there is a large number of PRSs in the EU territory, it is worthwhile to investigate and analyse the feasibility and performance of this system configuration. However, the use of flat-plate collectors in EU countries does not ensure that