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Techno-Economic Analysis of ORC in Gas Compression Stations Taking Into Account Actual Operating Conditions

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Abstract

Gas compressor stations represent a huge potential for exhaust heat recovery, currently under-exploited. Typical installations consist of multiple gas turbine units in mechanical drive arrangement, operated, most of the time, at part-load conditions and with limited conversion efficiency. In this context, this paper investigates the energetic-economic potential of ORC application in typical gas compression facilities, as innovative contribution with respect to literature. The ORC is designed to convert the gas turbines wasted heat into useful power. Additional power output can be used either inside the compression facility, reducing the amount of consumed natural gas and, consequently, the environmental impact, or delivered to the electrical grid. Taking into account real operation of gas turbines in a natural gas compression station, located in North America, additional generated energy and CO_2 avoided, thanks to ORC operation, are quantified. Two ORC arrangements, namely with and without intermediate heat transfer fluid, are proposed and the design performance are identified. Influence of topper cycle part load operations on bottomer section are quantified through an off-design thermodynamic evaluation. The goal of the performed analysis is to obtain a detailed scenario of the integrated system operation on yearly basis. Results, for a reference 50 MW compression station, show that the direct heat exchange configuration guarantees up to 66 GWh/year of additional electrical energy, saving up to $36*10^3$ tons/year of CO_2, while ORC investment costs can be recovered within 7 years of operation. The performed comprehensive investigation assesses the ORC as a techno-economic profitable technology to recover wasted heat in natural gas compression facilities.

Keywords: Organic Rankine Cycle; Gas Turbine; Natural Gas Compression station; techno-economic analyisis; Oil&Gas Applications;

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Nomenclature

CS	Compressor Station
CHP	Combined Heat and Power
DHE	Direct Heat exchange
GT	Gas Turbine
GHG	Green House Gases emissions
HC	HydroCarbon
HE	Heat Exchanger
IHTF	Intermediate Heat Transfer Fluid
ISO	International Organization for Standardization
NG	Natural Gas
NPV	Net present value
ORC	Organic Rankine Cycle
REG	Regenerative heat exchanger
SH	Superheating

Symbols

η	efficiency [-]
I_{TOT}	Total investment costs [$]
Ma	Operating and maintenance costs [-]
n	plant assumed operating life [years]
P	power output [kW]
Q	thermal power [kW]
q	discount rate [%]
R	Revenues [$]
AVA	available

1. Introduction

A preliminary Authors investigation on Organic Rankine Cycle (ORC) energy recovery potential, in the oil&gas sector [1], showed that the Natural Gas (NG) transmission and supply network represents a significant opportunity, comparable to cement, steel and glass industries. In this context, a fundamental role is played by NG pipelines infrastructure, where Compressor Stations (CSs) are used to guarantee the gas operating pressure throughout the network. Indeed, the NG compression process requires a huge amount of energy; it is usually supplied through Gas Turbines (GTs), electric motors or reciprocated engines, working as mechanical drivers. In case of GT drivers, a small fraction of transported NG is used as fuel. In order to ensure power capability to drive compressor units, the typical installation arrangement consists of multiple GT units with a potential of operating under part-load conditions. Specifically, redundant installed capacity ensures the necessary reserve power and the safe operation of the compressors. NG fueled engines and turbines generate heat as by-product. About one third of fuel primary energy input is converted into mechanical power; the remaining two-thirds are rejected as hot exhaust and, in case of engines, also in the cooling systems. In industrial or commercial Combined Heat and Power (CHP) applications, the heat is recovered and used to provide a useful output (such as hot water or steam for the utilities). Thus, CHP applications significantly improve the overall fuel conversion efficiency of the system. On pipelines, CHP is difficult to implement: no significant thermal energy needs are accounted and CSs are located in remote places, far from industrial or urban area. As a consequence, a significant portion of primary energy is discharged into the atmosphere with exhausts. Therefore, the possibility to exploit the GT wasted heat through an ORC represents a viable solution to: (i) increase the overall efficiency of a NG CS facility; (ii) generate additional shaft power that could be used inside the compression station or, as alternative, electric power directed to the grid, (iii) reduce the pollutants emissions. A previous review study of the Authors, on European Market, in [1] estimated that the electric power recovery potential of ORC applied to CSs is close to 1300 MW, energy generation is up to 10.43 TWh per year, avoided GHG emissions up to 3.7 million tons and avoided energy costs up to 934 million euro per year.

Several studies highlighted the main advantage of ORC compared to traditional steam cycle architecture, also addressing this bottomer technology as a performing solution for both low/medium and high/medium grade wasted heat applications [1-17]. Among organic fluids suitable for GTs and internal combustion engine exhaust gases exploitation, Cyclopentane has been identified as one of the most promising hydrocarbon fluid for large size applications [17, 18]; this fact is mainly due to its critical properties values (pressure equal to 45.1 bar and temperature equal to 238.6 °C) and high thermal stability limit (up to 300 °C). As pointed out in [19], ORC systems using Hydrocarbon (HC) as working fluids can feature several advantages in CSs applications compared to conventional steam cycle plants such as: (i) a more compact equipment thanks to Hydrocarbon lower specific volume; (ii) a reduction in expander size and air leakage potential thanks to HC higher condensation pressure values compared to steam at the same temperature; (iii) avoidance of expander erosion problems due to the dry proprieties of complex HC and, finally, (iv) the use of air cooled condenser: these feature make ORC application suitable also for remote locations, such as NG CSs.

Since NG networks represent a significant opportunity for energy recovery, currently under-exploited by industrial operators of this industrial sector, the ORC application is considered in the study.

In this context, the main contribution of this work, with respect to the available literature on the topic and as a further advancement of previous studies by the Authors on GT-ORC integration in CSs, is to provide a deeper techno-economic performance investigation of the ORC potential, in a real NG compression station. The case of a reference typical 50 MW NG compression station under actual operation is investigated. In details, two different GTs-ORC configurations (namely with and without intermediate fluid) are designed and thermodynamic performance are identified. Taking into account GTs part-load behavior during the year, the ORC cycles off-design operation are estimated. An energetic, economic and environmental analysis on a yearly base is carried out, to show the feasibility of ORC as heat recovery technology for gas compression stations.

2. GTs-ORC integrated system

2.1. GTs-ORC proposed waste heat recovery configurations

Two different thermal connection solutions between topper and bottomer sections are investigated in this study, namely with and without Intermediate Heat Transfer Fluid (IHTF). Figure 1 shows the proposed GTs-ORC arrangements: Case IHTF in Fig. 1 a) and Direct Heat Exchange (DHE) Case in Fig. 1 b). Both topper section layouts consist of two identical GT units operated in parallel and one left as back-up unit.

In IHTF Case (fig. 1a) ORC fluid and exhaust gases are kept separated thanks to a secondary loop. GT exhaust gases are used into four Heat Exchangers (HEs) in parallel (one for each GT machine), to heat the IHTF, which, in turn, transfers residual heat to the ORC fluid in the once-through boiler. In the DHE Case (fig. 1b) GTs exhaust are driven directly to two ORC once-through boilers. Thus, the DHE scheme simplifies the plant layout, decreases the heat transfer irreversibility and reduces the components costs. Pros and cons of the proposed layouts are summarized in previous investigations [17, 20, 21]. The subcritical ORC bottomer cycle consists of a single expander, an air cooled condenser and a pump. Both architectures also include a Regenerator (REG) heat exchanger that preheats the ORC fluid entering the boiler, exploiting the residual heat at the ORC expander outlet.

Based on previous investigations and industrial expertise [17, 18] Cyclopentane, has been assumed as working fluids in both layouts. Therminol 66 has been selected as the intermediate fluid in Case IHTF layout. The GT model assumed in the topper section is a General Electric PGT25, quite diffused in the oil&gas sector and, in particular, as mechanical driver in gas compression stations (e.g. the Feriana-Tunisia project, the Blue Stream Pipeline project from Turkey to Russia and the pipeline compressors used in the Sbikha-Tunisia line [22, 23]). The GT unit rated shaft power is close to 23.7 MW, with a corresponding efficiency of about 37 %. The available thermal power for each GT unit (Q_{AVA}) results close to 30 MW assuming to cool from 540 °C (corresponding exhaust temp.) down to 150°C the amount of exhaust gas mass flow rate (equal to 69 kg/s).

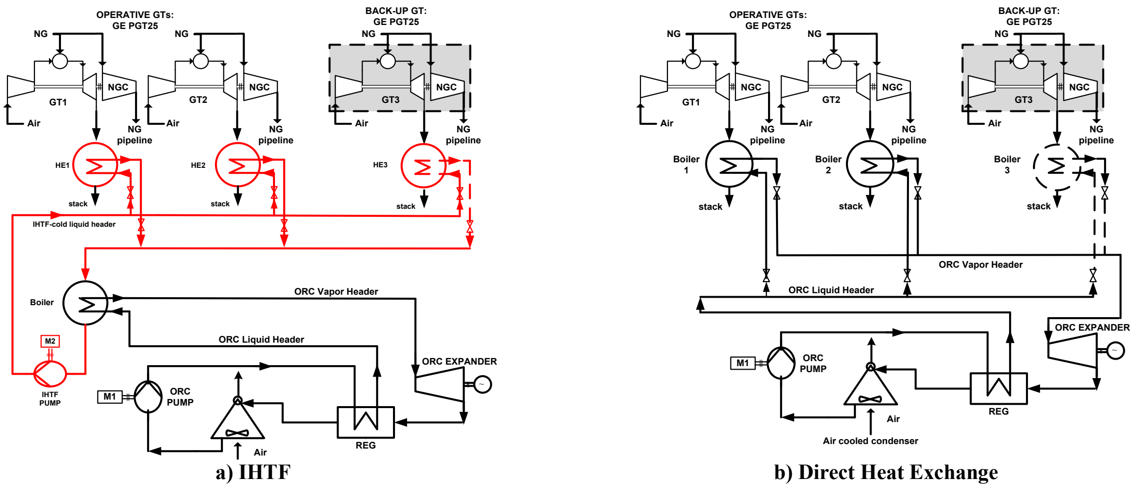

Figure 1: schematic of GTs-ORC waste heat recovery layouts

2.2. GTs-ORC assumptions based on actual NG CS operation

Based on GTs typical operation in a NG CS facility, the design of the ORC bottomer recovery cycle has been identified. The 2015 UK report [24] analyzed the operation of 192 GT units (33% working as mechanical drive units) installed in the oil&gas sector. From data collection, main results of the study highlight that: (i) part-load operation of machines, between 70- 50 % of rated capacity, occurs during the entire operation period; (ii) for reasons of both plant flexibility and security, load share operation (also named as spinning reserve and N+1 operation) is the normal operating philosophy: out of the 192 units in the database, 187 (97%) were operating in load share. Indeed, as confirmed by the report, load share operation means that units are commonly working at reduced capacity (even less than 70% of gas turbine manufacturers rated load) with a corresponding reduced conversion efficiency and a considerable amount of wasted heat. To evaluate ORC recovery potential in a specific application, one minute data of GTs actual operation in a NG CS located in North America has been considered. Figure 2 shows the load duration curve of GTs working as mechanical drivers during one year of operation. The GT units are operated under part load for about 7300 hours/year, while in the remaining periods the units are shut down. The inactivity hours are due to both units maintenance outage and no demand for compression in the station. The GT units operate between 80 and 60 % of their nameplate capacity for about 4000 hours/year. The minimum GTs load is higher than 45 %.

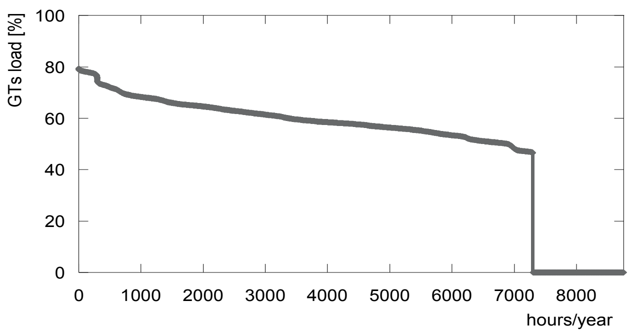

Figure 2: Gas turbines load duration curve in a natural gas compression station.

Based on the above considerations and in order to not over-size the bottomer components, the ORC cycle has been designed, considering GT units (see topper configuration in Fig. 1 a and b) at 80 % of their full load capacity. The design specifications assumed for the GTs-ORC integrated cycles are listed in Table 1. Most of these data are consistent with existing ORC large scale state-of-art products and also in line with Turboden typical operating parameters. More in details, based on manufacturers experience, a trade-off ratio between evaporative and critical fluid pressure has been selected, in order to maximize the cost-benefit concerns, equal to 0.76 for Cyclopentane (see Table 1). Practical considerations have been also applied to ORC maximum temperature value: the superheating degree max. value (calculated ad difference between superheated and evaporative temperatures) is selected according to specific fluid thermal stability limit. The isentropic efficiency of ORC expander is set equal to 0.85, in line with 10 MW size component. The condensation temperature is set equal to 35 °C (corresponding to a condensation pressure equal to 0.61 bar) assuming to use air cooled condenser with inlet temperature of 15 °C (ISO conditions). In order to guarantee a complete fluid condensation inside the condenser, a subcooling value equal to 5 °C has been assumed according to plants operative data. Pressure drops and heat losses at all the HEs are specified according to commercial values. Finally, the minimum gas turbine stack temperature after the waste heat recovery has been considered in the analysis equals to 150 °C.

Table 1: GTs-ORC design assumptions

GT load [% of nameplate capacity]	80	HE pressure drop, IHTF/ gas side [bar]	1.5/0.015
Inlet/outlet duct pressure losses [mbar]	10	REG effectiveness [%]	85
Minimum GT stack temperature [°C]	150	REG pressure drop ORC liquid/vapour side [bar]	1/0.55
ORC working fluid	Cyclopentane	Subcooling ORC outlet condenser [°C]	5
IHTF assumed	Therminol 66	Condensation temperature [°C]	35
ORC expander isentropic efficiency [%]	0.85	Condenser pressure drop, organic fluid side [bar]	0.1
ORC evaporative pressure-critical pressure ratio [-]	0.76	Air draft losses [mbar]	2
ORC max. superheating degree [°C]	96.5	Heat exchangers thermal loss [%]	1
Boiler pressure drop, organic fluid/ IHTF/gas side [bar]	2/1/0.015	Electro/mechanical efficiency [%]	97
IHTF maximum temperature [°C]	315	Pumps mechanical efficiency [%]	80
IHTF loop max. pressure [bar]	15	Pumps/Fun nominal isentropic efficiency [%]	60
pressure drop in IHTF loop [bar]	2	Miscellaneous GT aux. load [% of GTs power]	0.7

The design and off-design evaluation of GTs-ORC integrated cycles have been calculated by means of a commercial software package (Thermoflex [25]). Cyclopentane properties are evaluated according to the internal database Refprop [26]. The topper section has been simulated based on Thermoflex internal GTs library: thus, the off-design GT operation is evaluated according to the manufacturer derating curves. The ORC bottomer section is modelled using single components modules (i.e., heat exchangers, expander, pumps, condenser). Once the ORC cycle design is calculated, the off-design performance has been evaluated assuming sliding pressure operation for the expander, fixed geometry and area for the heat exchanger components.

Table 2 summarizes the design performance results of the GTs-ORC integrated plant layouts. The bottomer cycles are able to generate 12 and 11 MW of gross electric power output, respectively in the DHE and IHTF case. Subtracting pumps auxiliary consumption, net power output results close to 11.3 and 10.5 MW, respectively. It must be pointed out that the decrease in net power output for IHTF case is mainly due to additional pump consumption of the IHTF loop (see exact value in Table 2). ORC net electric efficiency results higher in case of DHE (24.2 %) compared to the IHTF configuration (22.2 %). Off-design bottomer performance are plotted in Figure 3 as function of GTs load, both in terms of normalized power output (Fig. 3a) and efficiency (Fig. 3b). As highlighted in figure, ORC power output decrease down to 60 % in correspondence to GTs minimum load (40 %), while efficiency variation is limited: 4 percentage point of reduction from max. to min. of GTs load.

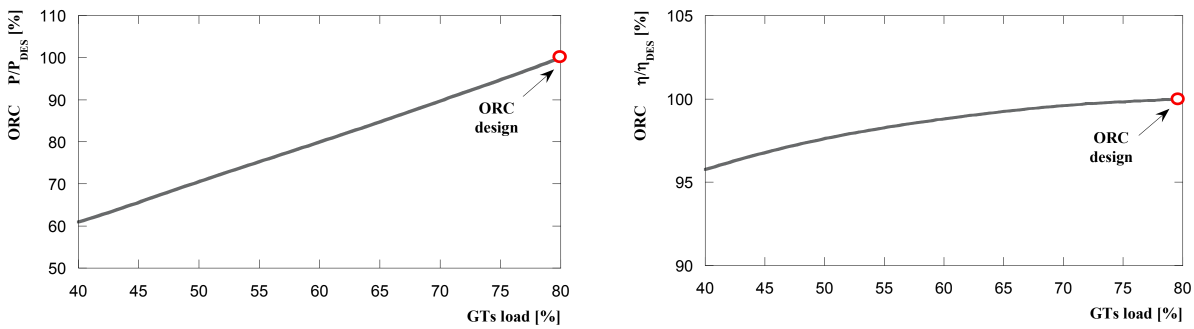

Figure 3: ORC normalized power output (a) and efficiency (b) as function of GTs load (Case DHE layout)

Table 2: GTs-ORC performance results for the analyzed Cases @ ISO condition

Performance results @ design conditions	DHE CASE	IHTF CASE
GTs topper shaft power output [kW]	37668	
Total fuel input power [kW]	104198	
GTs shaft efficiency [-]	0.362	
GTs total exhaust mass flow rate [kg/s]	128	
GTs exhaust temperature [°C]	490	
Bottomer cycle thermal power input [kW]	46856	47294
ORC turbine inlet pressure [bar]	34	34
ORC turbine inlet temperature [°C]	280	250
Condenser pressure [bar]	0.61	0.61
ORC fluid mass flow rate [kg/s]	80	84
IHTF inlet/outlet temperatures [°C]	-	130/315
IHTF fluid mass flow rate [kg/s]	-	112
ORC gross electric power [kW]	12039	11433
ORC Specific power [kJ/kg]	155	140
Thermal power to condenser [kW]	34593	35436
Turbine expansion pressure ratio [-]	56	56
Turbine expansion volume ratio [-]	35	38
Organic fluid/IHTF pumps consumptions [kW]	728/-	739/185
Air cooled condenser fun consumptions [kW]	953	977
Net ORC electric power output [kW]	**11311**	**10509**
Net ORC electric efficiency [-]	**0.241**	**0.222**

3. ORC application feasibility in a NG CS: yearly performance evaluation

Behavior of ORC, both configurations, has been analyzed during one year of NG CS operation, according to data presented in Fig. 2. The resulting ORC load duration curve is shown in Figure 4 in case of DHE configuration. As highlighted in figure, part load operation between 100 % and 60 % of rated capacity occurs for about 7300 hours/year. Average load during operative hours is equal to 80 % (corresponding to 9 MW in case of DHE layout) with an average electric efficiency close to 24 %. Yearly energetic and environmental results of ORC application as bottomer energy recovery cycles are summarized in Table 3 and Figure 5. The equivalent primary energy saved is calculated assuming as reference the electric efficiency of the PGT25 unit used as topper (equal to 36.2 % @ full load condition). The use of ORC, configurations DHE and IHTF, enable the saving of more than 182 and 170 GWh of NG per year, generating respectively 66 and 62 GWh/year of electrical energy. The total amount of CO_2 saved is up to $36*10^3$ tons/year. The DHE configuration achieves the best energetic results compared to intermediate fluid layout.

The performed economic analysis has been based on Net Present Value (NPV) method, calculated according to the following equation [27]:

$$NPV = \sum_{i=1}^{n} M_a \frac{R_i}{(1+q)^i} - I_{TOT} \quad (1)$$

where *n* represents the system lifespan assumed equal to 20 years, q is the interest factor (6 %), I_{TOT} is the total investment cost and R_i are the annual income. In the analyzed scenario, annual incomes are represented by fuel savings and avoided CO_2 taxes, as detailed in [27]. Operating and maintenance costs are accounted in the M_a non-dimensional factor assumed equal to 0.9. A sensibility analysis has been carried out varying the NG price, the CO_2 tax and the total investment costs associated with the bottomer cycle. NPV results plotted in Figure 6 refers to a fuel market price set equal to 0.09 \$/Sm^3 and a carbon dioxide tax of 56 \$/t$_{CO2}$, according to [27]. Total ORC investment costs, in line with typical 10 MW size technology, have been differentiated according to configurations in order to account for presence or absence of the IHTF loop: a value equal to 1500 $/kW and 2000 $/kW has been assumed for DHE and IHTF configurations, respectively. Results show that, due to a lower investment cost and a higher energy performance results, DHE case can achieve the best economic performance with a payback period equal to about 7 years. Overall obtained results prove the ORC technology as a techno-economic profitable solution to recover wasted heat in NG CS facility.

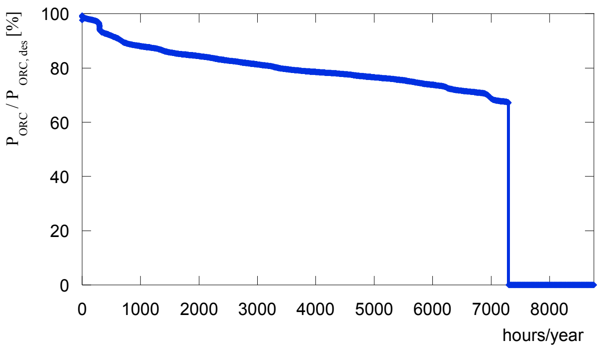

Figure 4: ORC load duration curve (DHE configuration).

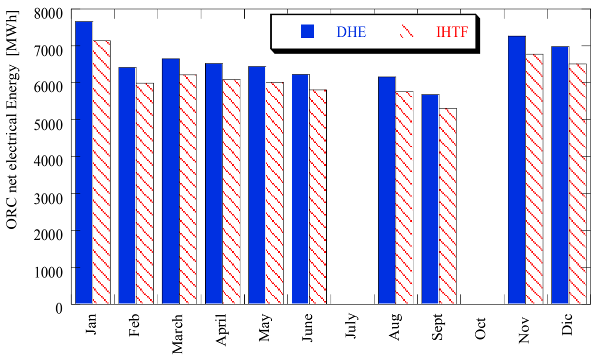

Figure 5: ORC generated net electric energy during the year

Table 3: GTs-ORC yearly results

Yearly results of ORC operation	DHE	IHTF
Average net Power output during operative hours [kW]	9084	8475
Average net electric efficiency during operative hours [-]	0.238	0.220
Generated net electrical energy [GWh/year]	66.03	61.60
Equivalent operating hours [h]	5838	5862
NG Primary energy saved [GWh/year]	182	170
CO_2 saved [tons/year]	36080	33661
ORC payback period [years]	7	11

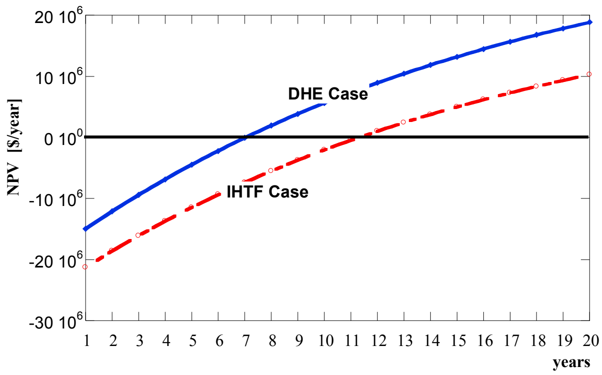

Figure 6: NPV behavior for DHE and IHTF configurations.

4. Conclusion

This paper presents results of a detailed techno-economic feasibility study of two different ORC configurations as energy recovery technologies to be implemented in a NG CS. Assumed configurations, namely with and without intermediate heat transfer fluid, have been designed, based on the yearly GTs operation profile. Once the ORC design performance have been identified, the performance of the integrated cycle have been evaluated, based on the NG CS real demand data, taking into account the bottomer off-design operation. The obtained results show that the direct heat exchange layout enables the saving of more than 182 GWh of fuel per year, generating up to 66 GWh/year of additional electrical energy. The total amount of CO_2 saved is up to $36*10^3$ tons/year. The performed economic analysis, based on the NPV method, shows that the ORC investment costs can be recovered within 7 years of CS operation. The performed comprehensive investigation assesses the ORC as a techno-economic profitable industrial technology, capable to recover significant amount of wasted heat in NG compression facilities.

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