KASDI MERBAH UNIVERSITY OUARGLA
FACULTY OF APPLIED SCIENCES
Department of Mechanical Engineering

Dissertation with a view to
obtaining the ACADEMIC
MASTER'S DEGREE

Field: Sciences and Technologies.

Major: Mechanical Engineering

Specialty: Energetic

Presented by:

Rabah Ghettas &Gana Khalil

Theme:

The integration of trigeneration system producing power, heat and cool into a compressor station

Publicly supported the:12/06/2023

In front of the jury:

President :	Mr A. GOUAREH	MCA	University Kasdi Merbah - Ouargla
Examiner :	Mrs H. BENADDI	MAA	University Kasdi Merbah - Ouargla
Promoter :	Mrs B. RECIOUI	MCB	University Kasdi Merbah - Ouargla

Year: 2022/2023

Dedication

I dedicate this modest work to: Those who are the dearest in the world, my parents, to whom I will never manage to express my gratitude and my gratitude, for their love, support them throughout my studies. To my brothers Soulmates To the whole family to all my friends for their support

Acknowledgment

First of all, we thank God Almighty for His favor and guidance, who gave us the opportunity and strength to do this work.

We would like to thank our teacher and supervisor **Dr. Recioui** for her valuable guidance and feedback. By making us benefit from her great advice and skills in the field of mechanical engineering.

We would like to express our sincere thanks to the workers and engineers at Berkawi compressor station, especially **Mr. Bilal** and **Mr. Boubaker** for their support, assistance and valuable information about the gas turbines.

We express our gratitude to the members of the Committee of Examiners, namely, **Mrs. Benaddi** and **Mr. Gouareh,** for their acceptance to read and examine our dissertation, to agree to judge this work, and for the honor of chairing the jury.

We would like to thank all our professors in the Department of Mechanical Energy at Kasdi Merbah University.

Last but not least, a big thank you to our families and friends at the university whose endless encouragement and support did not stop throughout the preparation of my work.

Abstract:

The triple generation system uses only one primary power supply, while providing power, heating and cooling simultaneously. This primary source can be represented by either fossil fuels or some suitable renewable energy source (biomass, biogas, solar energy, etc.). Algeria's main generating fields can be found at the power stations, compression stations (CS) and pumping stations (PS) of the national network of liquid hydrocarbons and pipelined gas transportation. Sonatrach's Pipeline Transmission (PTB) branch operates more than 300 gas turbines that equip compression and pumping stations in its network to develop a total capacity of more than 2,891,643 MW. Each plant has an average of 3 single-cycle gas turbines with an efficiency of 32% to drive compressors and pumps. The objective of this work is to estimate the potential for energy, heat and cooling production by integrating tertiary generation at the Barkawi compressor station, energy study, and environmental and economic performance evaluation. A numerical study was conducted and the following results were obtained: The amount of electrical energy is estimated at 57.95MWh, the amount of heat is 27094.04KJ, and the amount of cold is 30964.61KJ. Its value is 17%, we can consider this project a success

Keywords: Algeria; compressor station integrated generation system.

Résumé :

Le système à triple génération utilise une seule source d'alimentation principale, tout en fournissant simultanément de l'électricité, du chauffage et du refroidissement. Cette source primaire peut être représentée soit par des combustibles fossiles, soit par une source d'énergie renouvelable appropriée (biomasse, biogaz, énergie solaire, etc.). Les principaux champs de production algériens se trouvent dans les centrales électriques, les stations de compression (CS) et les stations de pompage (PS) du réseau national de transport des hydrocarbures liquides et du gaz par conduites. La branche Pipeline Transmission (PTB) de Sonatrach exploite plus de 300 turbines à gaz qui équipent les stations de compression et de pompage de son réseau pour développer une capacité totale de plus de 2 891 643 MW. Chaque usine dispose en moyenne de 3 turbines à gaz à cycle unique avec un rendement de 32 % pour entraîner les compresseurs et les pompes.

L'objectif de ce travail est d'estimer le potentiel de production d'énergie, de chaleur et de froid en intégrant la production tertiaire à la station de compression de Barkawi, l'étude énergétique et l'évaluation des performances environnementales et économiques. Une étude numérique a été menée et les résultats suivants ont été obtenus : la quantité d'énergie électrique est estimée à 57,95 MWh, la quantité de chaleur est de 27 094,04 KJ et la quantité de froid est de 30 964,61 KJ. Sa valeur est de 17 %, nous pouvons considérer ceci projet réussi

Mots clés : Algérie ; système de génération intégré de station de compression.

Contents

Nomenclature

Symbols	*Definition*	*Unit*
η	Efficiency	%
E	Electricity	**Wh**
$F_{emission}$	Emission Factor	**g CO_2/kWh**
E_{gener}	Energy generated	**Wh**
H	Enthalpy	**kJ/kg**
S	Entropy	**kJ/kg.k**
Cp_g	Heat capacity of the exhaust gas	**kJ / kg. °C**
Cp_{water}	Heat capacity of the water	**kJ / kg. °C**
Q	Heat exchanged	**W**
A	Heat transfer surface area	**m^2**
ΔTLM	Log mean temperature difference	**K, °C**
PCI	Lower calorific value power	**MJ/kg**
$\dot{m}_g$	Masse flow rate of the exhaust gas	**Kg/s**
$\dot{m}_f$	Masse flow rate of the fuel	**Kg/s**
$\dot{m}_s$	Masse flow rate of the steam	**Kg/s**
$\dot{m}_{water}$	Masse flow rate of the water	**Kg/s**
P	Pressure	**Pa, bar**
O_{CO2}	Saved CO_2 quantity	**Tons**

SCNG	Specific Consumption of natural gas	**m^3/kWh**
T	Temperature	**K, °C**
P	the density	**Kg/m^3**
U	The overall heat transfer coefficient	**W/m^2. K**
$\sum Pi_{Load}$	Total active load	**W**
TCNG	Total Consumption of natural gas	**m^3**
$\sum \mathrm{Oi}_{Load}$	Total reactive load	**Var**
W	Work	**J**
Q	thermal Energy	**KJ**
h	hour	**h**
l_0	Investissement	**USD/KWh**
C_{fm}	The operation cost of trigeneration systems	**USD**
C_{fu}	The annual fuel cost	**USD**
C_{ma}	The operation and maintenance costs	**USD**
R_{al}	The economic revenues	**USD**
R_e	The electricity revenues	**USD**
R_h	The heating revenues	**USD**
R_C	The cooling revenues	**USD**
T_J	The static investment payback period	**Year**
T_d	The dynamic investment payback period	**Year**
A_t	The annual net income in year t	**USD**
F_t	The cash flow in year t	**USD**

i_0	The discount rate	%
δ_1	The fuel calorific value	**KJ/m^3**
d	The annual supply days	**day**
NPV	The net present value	**USD**
IRR	The internal rate of return	%
P_f	The fuel price	**USD/m^3**
P_e	The electricity price	**USD/KWh**
P_h	The price of heating	**USD/KWh**
P_c	The price of cooling	**USD/KWh**
Q_c	The cooling supplies	**KW**
Q_h	**The heating supplies**	**KW**

Abbreviations

Abbreviation	Definition
BFS	Backward/foreword sweep
CC	Combined cycle
CHP	Combined heat power
CO	carbon monoxide
CS	Cogeneration systems
DG	Distributed generation
FERC	The Federal Energy Regulatory commission
GHG	greenhouse gases
GT	Gas turbine
HRSG	Heat recovery steam generator
ICE	Internal combustion engine
ISO	International Organization for Standardization
LPG	liquefied petroleum gas
NOX	nitrogen oxides
PS	pumping stations
PTB	The pipeline transport branch
SC	compressor station
SO_2	Sulfur dioxide

Sonatrach	**National Company for Research, Production, Transport, Processing, and Marketing of Hydrocarbons**
Sonelgaz	**National Electricity and Gas Company**
ST	**Steam turbine**
Toe	**Ton of oïl equivalent**
TWh	**Terawatt hour**
COP	**Coefficient of performance**
CCHP	**combined cooling, heating and power**
HRH	**Recovered heat for heating**
HRC	**Recovered heat for cooling**
AC	**Absorption chiller**
PGU	**Power generation unit**

List of tables

List of figures

General Introduction

General Introduction

Trigeneration system is generally known as producing heat, electricity and cooling simultaneously. The growing interest in energy efficiency, saving the environment and reducing greenhouse gas emissions has shown the desire to explore and use tertiary generation systems as a solution to economic and environmental problems.

Under the current system of centralized electricity generation, electricity is mainly produced in large generation plants, and then transmitted through distribution networks to the final consumers. However, the modern pursuit of energy efficiency, reliability and reduction of greenhouse gas emissions has led to the exploration of possibilities for changing the existing electricity generation system and increasing its overall performance. In this context, a tertiary generation system is one of the best candidates to complement or even replace the existing pattern, where electricity is produced close to the point of use.

The spread of decentralized electricity production has been greatly achieved nowadays. And by increasing the use of electricity from both renewable and fossil sources, tertiary generation has become part of electricity production in line with this trend.

In Algeria, global energy consumption has been increasing rapidly in recent decades, and the household sector accounts for more than a third of global energy consumption. This growth has been stalled since 2005 due to the stable reserves of oil and gas, which is a serious indicator of the supply and demand problem. And with projections of increasing population and housing, which are the main drivers of consumption in the housing sector, this problem could become more serious. Therefore, Algeria should focus on developing and adopting a tertiary generation system as part of its solutions to energy problems and providing a green and sustainable future.

Chapter 1 provides an explanation of the tertiary generation system and also presents its applications and classifications.

The aim of Chapter 2 is to acquaint the reader with the procedure followed Calculation of the total efficiency of the combined cycle system, first we talk about The compressor station (Al-Barkawi SC3 station) and how it works, after that we calculate the efficiency of the gas turbine, and then we use the parameters obtained from the station control room to calculate CC efficiency and studying the percentage of meeting station requirements

Chapter 3 introduces the System Economic Analysis of Integrated Trigeneration Cooling, Heating, and Electricity (CCHP) System is a comprehensive framework for evaluating the economic aspects and potential financial benefits of implementing a CCHP system. CCHP, also known as ternary generation, is a highly efficient power generation system that simultaneously produces electricity, heating and cooling from a single power source

Chapter I: The Trigeneration system

I-1Introduction

Most conventional power generation systems are based on fossil fuels, which result in a huge amount of greenhouse gases (GHG) emissions. Hence, it is need of the day to explore the renewable sources or to use the low-grade waste heat from the power generation process for heating and/or cooling. It will be one of the solutions to save the energy squandering, and thus trigeneration technologies are quite relevant in present perspective.

Present study shows that the degree of improvement of a trigeneration system is sensitive to the performance and operating parameters of each unit and the approach used to integrate these units into the single system. Therefore, energy, exergy, and environmental study of any proposed system are important to assess the system performance and to examine the possible degree of improvement in the system. The exergy analysis helps in identifying and quantifying the sources of the irreversibility in the system that are associated with each component. The environmental analysis shows how much reduction in CO_2 emissions when the trigeneration system is used, as compared to a simple electrical power system. Economical study reports how generation of power locally and its consumption from the distribution companies and using it for the cooling and heating most of the times proves to be costlier .

I-2 Definition of Trigeneration system

As its name suggests, trigeneration provides a third form of energy (cooling energy) in addition to heat and electricity. The systems of trigeneration (also called production systems combined cold, heat and power (CCHP)) generally combine cogeneration units and chillers to produce electricity, heat and cooling energy in one process. Waste heat is converted into water refrigerated, by absorption technology or adsorption (Energiewende, 2015)

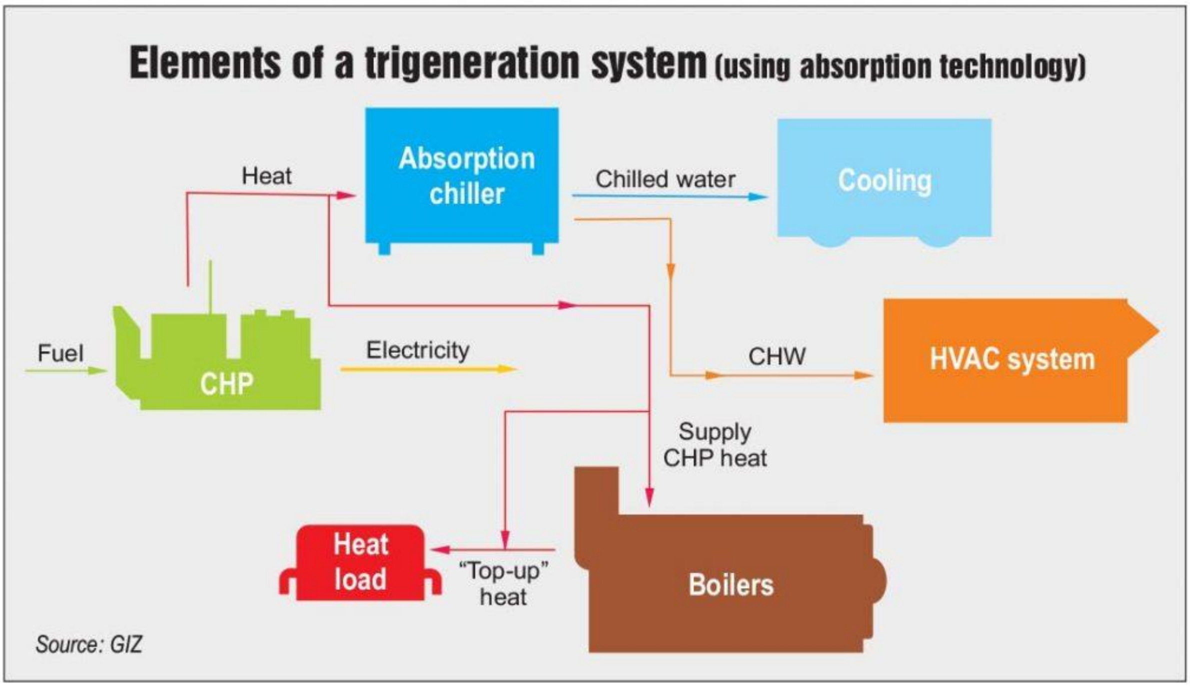


Figure I 1: Elements of a trigeneration system (Project.)

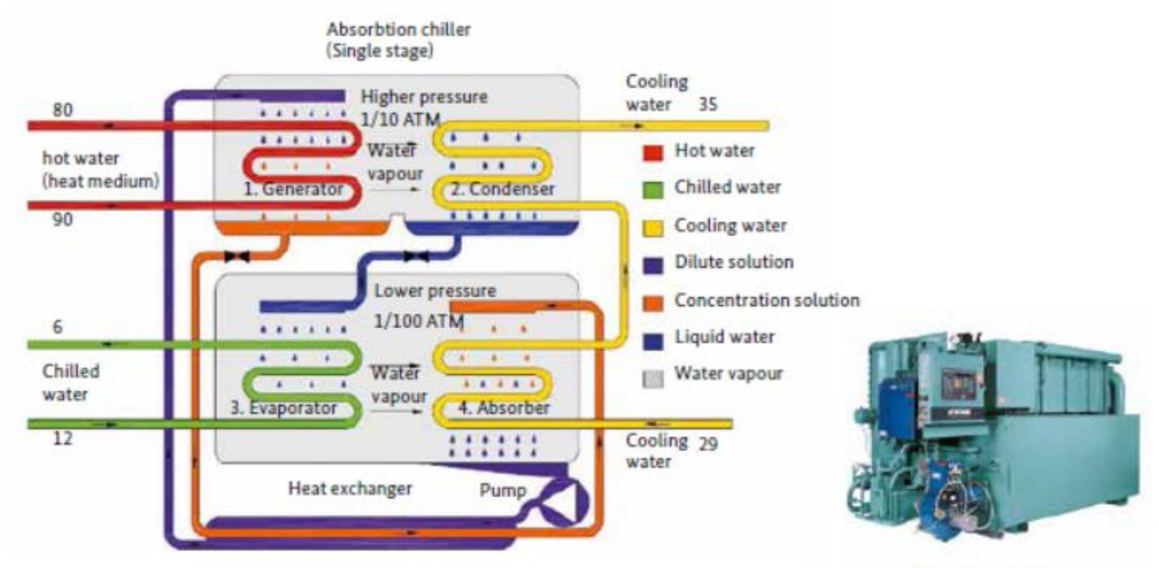
As shown in Figure 1, the system of trigeneration adds a technology of cooling in the cogeneration process, in the form of cooling components absorption (or adsorption where applicable). There heat is used to produce energy cooling.

Trigeneration systems further optimize the higher the efficiency of cogeneration plants using the (residual) heat produced to heating and/or cooling. They also improve flexibility in the use of waste heat because the process can be adapted to variations seasonal changes in heating energy demand and cooling

I-3 The principle of Trigeneration

Absorption technology is a proven and widespread thermal chiller technology, especially within the trigen market. The technology has been used for many years to utilise low-quality waste heat from power generators, including cogen systems for cooling demand. Due to the fact that absorption chillers often use corrosive lithium bromide (LiBr) salt as a refrigerant, these systems usually have high maintenance costs as a consequence of corrosion effects.

Absorption chiller capacities typically start from several hundred kW, ranging up to multi-MW chillers. Specialized products even start from capacities as low as 5 kWel up to 20 MWel and more for high cooling energy demands. Figure 7 next page shows the functional principle of absorption technology on the left and a small- to medium-scale 700 – 2,460 kWel absorption chiller on the right.



Absorption principle

Absorption chiller, 700 – 2,460 kW_{el} capacity

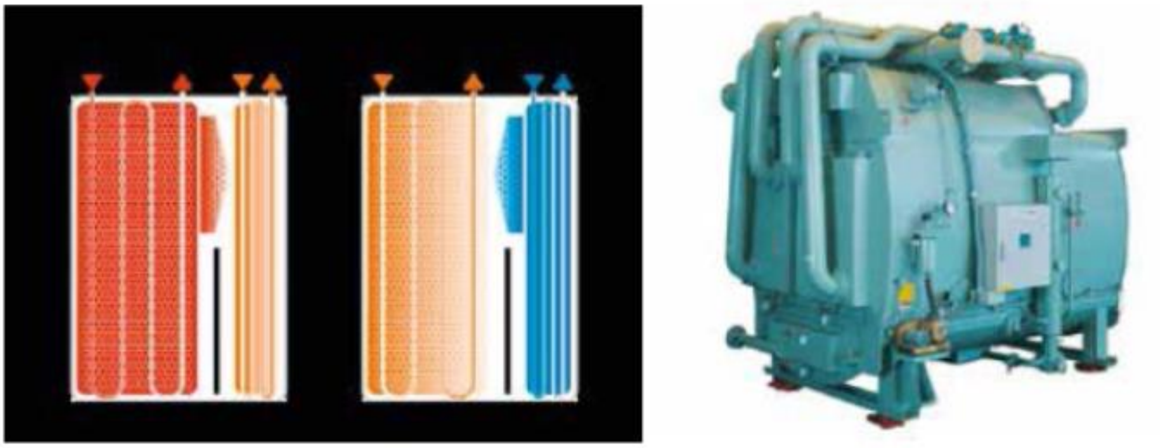
Figure I 2: Absorption Process (Pvt, 2013) (CDU, 2013)

Adsorption technology is relatively new, and installations are not yet widely used for trigen applications. Although there are similarities between absorption and adsorption refrigeration, the latter is based on the interaction between gases and solids. Adsorption chillers operate on the principle of adsorption rather than absorption, namely that molecules adhere to the surface of an adsorbent rather than being dissolved.

The adsorption chamber of the chiller is filled with a solid material (for example zeolite, silica gel, alumina, active carbon and certain types of metal salts), which in its neutral state has adsorbed the refrigerant (in most cases water). When heated, the solid desorbs (releases) refrigerant vapour, which subsequently is cooled and liquefied. This liquid refrigerant then provides its cooling effect at the evaporator, by absorbing external heat and turning back into a vapour.

In the final stage the refrigerant vapour is (re) adsorbed into the solid. Once the material is saturated, adding heat into the supply will again regenerate it. This process results in intermittent cooling (Solutions., 2014)

As an adsorption chiller requires no moving parts, it is relatively quiet. ((CERC), 2014) Moreover, adsorption chillers are less energy and maintenance intensive and consequently less costly than absorption processes. Simplicity of operation makes the adsorption chiller technology reliable, safe and attractive for trigen applications. Capacities of adsorption chillers range from 5 kWel to 2 MWel; tailored solutions can have even higher capacities. Figure 8 illustrates the functional principle of the adsorption process as well as a small-scale adsorption chiller.



Adsorption principle

Adsorption chiller, 50 kW_{el} capacity

Figure I 3: Adsorption Process (Factbook, 2014) (CODE2, 2014)

The chiller works without hazardous substances such as ammonia or lithium bromide, and can be operated in a wide range of temperatures between 50° and 90°C and without corrosion. The adsorption process allows stable operation and chilled water output of about 3°C to 9°C, even with fluctuating hot water temperatures and flow rates that are common for waste heat recovery applications.

I.4 Classification of Trigeneration technologies

I.4.1 Classification by size

Trigeneration applications are categorized into micro, small-scale, medium and large-scale systems, whilst the size range of these categories are under 20 kW, from 20 to 1 MW, from 1 to 10 MW and above 10 MW, respectively.

The capacity of distributed CCHP systems ranges from less than 1 kW in domestic dwellings to more than 10 MW in hospitals or university campuses, and as much as 300 MW to supply energy to a district of a city.

I.4.2 Classification by applications

According to applications, the CCHP systems are classified broadly as:

1. Traditional large-scale predominantly CHP systems in centralized power plants or large industries.

2. Relatively small/micro capacity CCHP units in commercial, institutional, residential and small industrial sections

I.4. 3 Classification by type of prime-mover

Prime-movers based on thermodynamic cycles concerns both internal and external combustion technologies. In micro and small-scale, residential, commercial and institutional applications, the main devices currently used are Internal Combustion Engines (ICEs) and microturbines.

Traditional large-scale centralized power plants or large industries have configurations based on either steam turbine, or combustion turbines. Systems not based on thermodynamic cycles are under development, and mainly concerns stirling engines, fuel cells, organic rankine cycle (ORC) and renewable energy systems, such as biomass, solar and wind, with potential to achieve high efficiency and low emission levels .

Reciprocating ICEs, steam turbines and combustion turbines still make up most of the gross capacity being installed . In addition, fuel cells, stirling engines and microturbines, mainly gas driven, present a promising future for prime movers .

I.4.4 Classification by sequence of energy

These can be classified as either a topping or a bottoming cycle system. In a topping cycle, the supplied fuel is first used to produce electricity and then thermal energy which is the by-product of the cycle, is recovered. It is widely used method of co and trigeneration.

In a bottoming cycle, first high-temperature thermal energy is produced by the combustion of fuel. Then, the heat rejected from the process is recovered to generate electricity using a turbine

I-5 Trigeneration benefits

1.5.1. Possibilities for refrigeration

**Absorption chillers:*

- Operation with hot water
- Operation with steam
- Direct heat through combustion

**Compression-type refrigeration machines:*

- Direct drive power
- Electrical drive power

I-6 Trigeneration applications

- **Commercial buildings**—office buildings, hotels, nursing homes, retail
- **Residential**—multifamily buildings, co-ops, planned communities
- **Institutions**—colleges and universities, hospitals, prisons, military bases
- **Municipal**—district energy systems, wastewater treatment facilities, schools

- **Industrial facilities**—chemicals, agriculture, ethanol, pulp and paper, food processing

I-7 Advantages of trigeneration systems over conventional refrigeration technology

- Operated with heat, utilizing relatively inexpensive "excess energy"
- Produced electricity can be fed into the public grid or used to cover electricity requirements of the plant
- During cold seasons the heat can be utilized to cover heat requirements
- No moving parts in absorption chillers, no wear and therefore low maintenance expenses
- Noiseless operation of the absorption system
- Low operating costs and life-cycle costs
- Water as refrigerant, no use of ozone-damaging substances

Absorption-type refrigeration technology offers the most established and economic solution for
reduced emission, air conditioning systems.

I-8 Conclusion

The tertiary generation system developed in this paper is an effective option to be evaluated in the planning and design of a new power system with demand for electricity, heating and cooling.

Active analysis shows high values for both global thermal efficiency and equivalent electrical efficiency. The initial energy saving percentage is about 23%. The economic analysis also results in a profitable investment.

Chapter II: Integrating the Trigeneration system in Berkaoui compressor station

II-1 Introduction

In this chapter we will give a brief description of the compressor station and give a special insight into the Barkawi compressor station (SC3), we will focus on the PGT2500 gas turbine, and we will use the parameters obtained from the station's control room to calculate the efficiency of the gas turbine.

After finding the efficiency, we will analyze the Gas Steam Combined Cycle (GT-ST) by calculating the heat exchanged through the components of the cycle. We will also calculate the amount of heat and the amount of cold that we can extract from the tertiary generation system. Finally, we will find the combined cycle efficiency and CO_2 emissions and we compare it to the efficiency of ordinary gas turbines. In this study all known properties and equilibrium equations of heat, mass, energy and entropy were integrated using Microsoft Excel.

II-2 Berkaoui compressor station

II.2.1 Geographic location

The HAOUD BERKAOUI region represents one of the ten (10) main hydrocarbon producing areas of the Algerian Sahara. On the RN° 49 road known as oil tankers linking Ghardaïa to Hassi Messaoud, and 35 km south-west of Ouargla, a crossroads indicates the presence of an oil field, this is the region of HAOUD BERKAOUI.

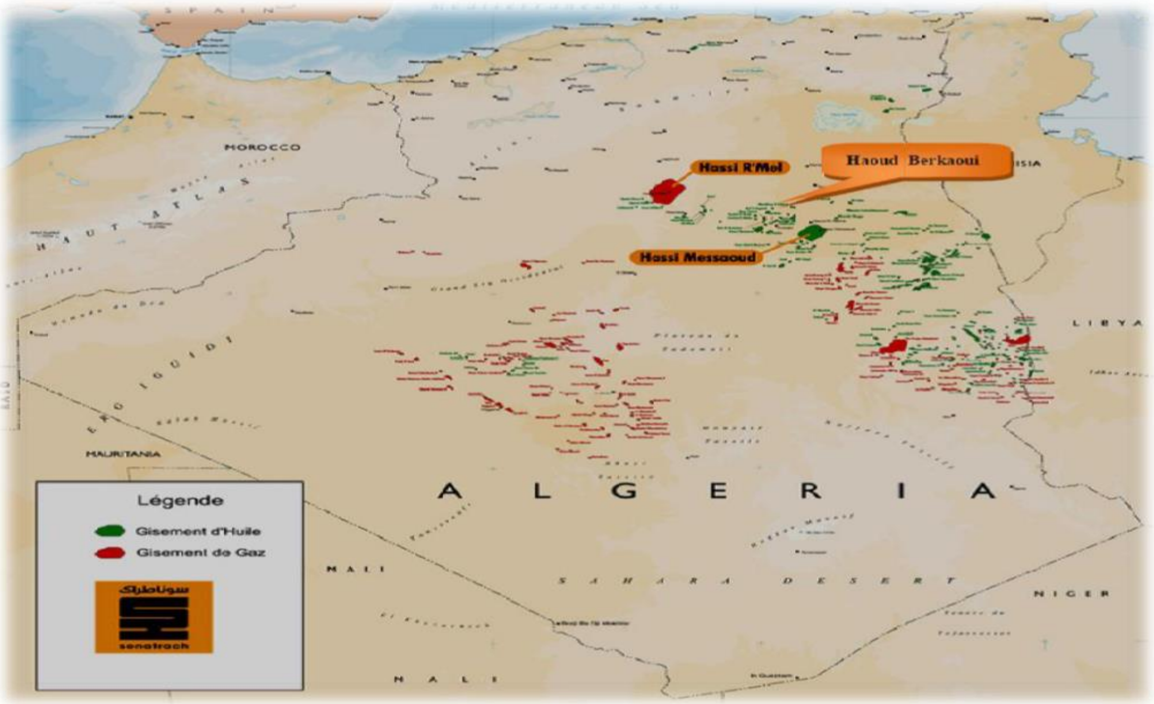


Figure II 1:Geographic location of the HAOUD BERKAOUI region (SONATRACH., 2013)

This region is located 140 km from HASSI Messaoud, 770 km south of the capital (Algiers). It is very important because of its share of the country's hydrocarbon production. It extends from the south-east of Ghardaïa to the extreme Boukhzana field, near the Touggourt road. (ilyas, 2020)

II.2.2 History of the region

The regional office of Haoud Berkaoui is located in the commune of Rouissat, 30 km from the capital of the wilaya of Ouargla. The region was managed by Hassi Messaoud until 1977, the year in which it became autonomous.The geophys ical studies carried out in the Ouargla region revealed the existence of two (02) structures called: Haoud Berkaoui and Benkahla, both located on an operating surface of 1600 km².

To date, 100 wells are in operation, spread over all the fields, including 73 gas lift wells and 51 blowout wells. The other wells, 27 in number, are water injection wells to maintain the pressure. Cumulative production since the start is 86 million m3, for reserves in place of 472 million m^3. All the quantities of recovered oil and gas are transported to the various production centers in the region. The main activities of the region are:

- production of oil and condensate.
- the production of associated gas (sale gas and gas lift).
- water injection.

Oil production is connected to 28″ Haoud El Hamra/Arzew by a 10″from the production centers of Haoud Berkaoui (production of Haoud Berkaoui and Benkahla) and an 8″ from the center of Guellala (production of Guellala, Northeast Guellala and the periphery). The sale gas production is conveyed by a 12″ pipe connected to the 48″ gas pipeline going to Hassi R’mel.

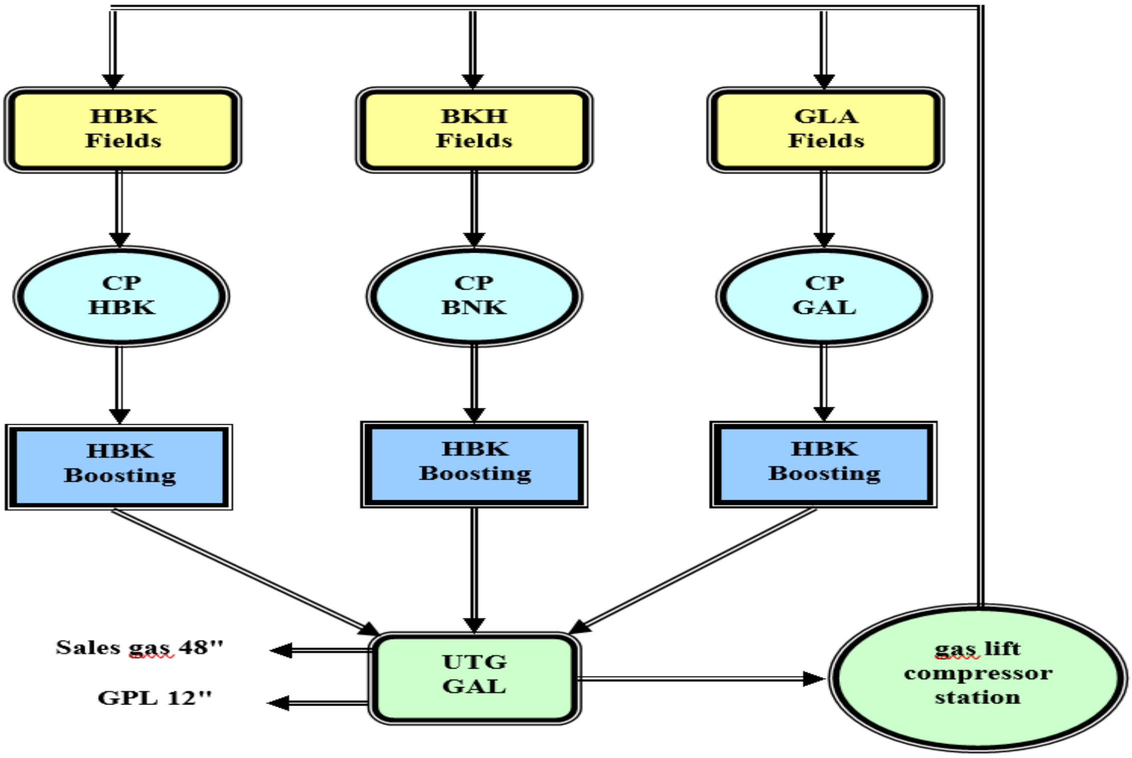


Figure II 2:The organization chart of the fields of the region

LPG production is routed to the 12″ Hassi R'mel gas pipeline through a 4″ pipe. There are three main production centers located in Haoud Berkaoui, Benkahla and Guellala.

II.2.2.1. HAOUD BERKAOUI's field

Covering an area of 175 km², this field discovered in March 1965 by the CFPA (French Algerian oil company) by drilling the OK101 well, is located at the top of the anticline.

This deposit was put into production in January 1967. HBK production consists of an oil separation unit with a capacity of 8,000 m^3/d, a storage autonomy of 13,000 m^3, a of gas boosting of 1 million m^3/d, and a water injection station unit at a rate of 6,000 m^3/J.

II.2.2.2. BENKAHLA Field

The Benkahla deposit was discovered in November 1966 by the same company (CFPA) by drilling well OKP24.

Covering an area of 72 km^2, this Benkahla production center is made up of a 5,000 m^3/d oil separation unit and a 560,000 m^3/d gas boosting unit, the entire production of Benkahla oil is shipped to the HBK production center.

II.2.2.3. The Field of GUELLALA

This deposit was discovered on October 28, 1969 by the drilling of GLA1, its commissioning in February 1973. It covers an area of 35km^2, with an average depth of 3500m. Currently, the production center consists of an oil separation unit with a capacity of 7,000 m^3/d, a storage unit of 15,000 m^3/d, and a gas boosting unit of 762,000 m^3 /d.

This station is also equipped with a gas treatment unit of approximately 2.4 million m^3/d. Its recovery capacity is estimated at 500 tonnes per day of LPG and 90 tonnes per day for condensates. The latter is accompanied by a gas compression unit at 75 bars with a capacity of 1,660,000 m^3/d, for the gas lift needs of wells in the region, the remaining volumes being sent to Hassi R'mel by the gas pipeline, GR1. Since its commissioning in 1992; 134 million m^3 of dry gas were thus shipped to Hassi R’mel, to which are added 429,000 tonnes of LPG.

II.3 Compressor station unit

The current **GUELLALA** compressor station layout represents the starting point of this study. It consists of two Turbo- Compressor (TC) groups, often called turbochargers, each of them made of a gas turbine which is mechanically driving a centrifugal compressor, referred to as TC-1, TC-2 . The TCs are placed in parallel and, as previously mentioned, have the task to increase the gas pressure from 50/55 bar to 70/75 bar. The two TC-1 and TC-2 groups are based on a SOLAR MARS 100-15000S gas turbine, 10MW mechanical power. them are open cycle gas turbines, without any heat recovery from the exhausts. This design choice depends on the operating discontinuity of the groups, which does not justify the placement of heat recovery boilers on the exhaust gases. In fact, the recovery units would be subject to considerable thermo-mechanical stresses and thus to a short life-time. (Paolo Silva, 2018)

The gas turbine groups burn a small fraction of the pushed natural gas. This gas must be heated from the network temperature of about 10/15 C up to a minimum safety value equal to 40 °C before entering the TC combustion system and ultimately the combustion chamber. As previously mentioned, this process is necessary in order to avoid the formation of liquid drops or hydrates that could clog the fuel distribution system, erode the nozzles of the combustor or lead to an abnormal combustion in the Machine.

Gas preheating is carried out by using hot water produced by natural gas boilers. Such preheating of the inlet gas could theoretically be increased up to about 140 °C for the largest group, and to 90 °C for the two smallest gas turbines, in order to achieve a better process integration and reduce primary energy consumptions.

The too machines are operated in a cyclic sequence, in order to have a similar number of operating hours and properly schedule their maintenance.

II3.1 Compressor station yearly data

The consumption of the GUELLALA station, in terms of electricity, heating and cooling load, has been derived from the data provided by Sonatrach which refer to the period 2010e2012. The total electricity and gas consumptions as well as the gas turbine operating time are available; however it is not possible to accurately distinguish the share of overall energy consumption, both for gas and electricity, among the several electricity, cooling and heating usages. For this reason, all the equipment of the compressor station have been split into two large categories: (i) consumptions related to the three TCs groups, which occurs only while the turbochargers are running, and (ii) base load utilities. Starting from electricity bills and operating datasheet of the TCs, it was possible to separate the electrical consumptions related to the operation of gas turbines from those related to the base load.

Then, from the base load consumption, it was possible to roughly identify the daily electrical demand for lighting, based on the information on the daily hours of darkness throughout the year, and the demand for the electric chillers, by means of a seasonal estimate of the cooling load. (Paolo Silva, 2018)

A similar procedure was performed to derive the thermal demand from the gas consumption. In this case, heat required to cover the thermal demand of the buildings could be separated from the one required by the TCs and estimated according to the thermal power balance $Q = m*Cp*\Delta T$, where m_ [kg/s] is the mass flow rate of NG to be preheated, derived from turbines characteristic curves at different ambient conditions, cp [kJ/kg K] is the natural gas specific heat at constant pressure and ΔT [°C] is the required change in temperature, from 10 °C to 40°C in winter, from 12 °C to 40 °C in mid-season, from 15 °C to 40°C in summer.

II-4 Proposed solution

After assessing the overall compressor station energy demand, the analysis has been focused on proposing a design improvement that is at the same time reasonable to implement and able to lead to a reduction of both plant operating costs and primary energy consumptions, thus carbon dioxide emissions. The selected approach shall take into account the fact that this compressor station is working on irregular bases, with many startups and shut downs, so that for instance it is not suitable to the installation of heat recovery systems on the turbines

The proposed solution to improve the compression station performance both economy-wise and environmentally-wise is the adoption of a trigenerative plant fulfilling the station loads; a solution which is also unique because, to the knowledge of the authors, it is not present in literature for this kind of application. The fulfillment of the electric, thermal and cooling load of the compressor station will be provided, instead of the boilers and compression chillers, by cogenerative units which will feed the thermal and electric load and also the cooling load by means of absorption chillers. It is well known that CCHP, when properly designed and scheduled, can lead to substantial reduction of primary energy consumptions, thus reducing the operating costs. In this case, once the solution has been designed, its optimal scheduling has been determined by means of heuristic optimization models as the ones described by Bischi et al. for cogenerative (Bischi A, 2016) and trigenerative solutions (Bischi A, 2014)

A simple cogenerative solution, also known as Combined Heat and Power (CHP), sizing the plant in order to match the heat load would not be able to support all the electricity production because the aforementioned energy requests feature a relatively high electricity-to-heat ratio (nearly 1.2). In fact, considering for example the typical efficiencies of cogenerative reciprocating engines, in the few hundred-kW range (η_{el}= 0.35; η_{th} = 0.55, with an electricity-to-heat ratio close to 0.6, it is clear that a strong integration with the grid would be necessary to meet the electricity demand. In addition, during summer the thermal load would drop to unsustainable values, under the technical minimum allowed by the engine (typically requiring to run above 50% of the nominal load due to environmental constraints, namely nitrogen oxide emissions).

On the other hand, a CHP unit sized for the electrical load would be largely inefficient, with a too large amount of dissipated heat: the produced heat, in fact, would be considerably greater than the thermal demand. Therefore, ensuring the installation of a CHP unit that is both efficient and technically feasible requires to modify the plant layout.

In order to tackle the abovementioned challenge, the adoption of a trigenerative solution is proposed, with the introduction of an absorption chiller that partially substitutes the existing compression chillers. The addition of an absorption chiller, in fact, modifies the ratio between heat and electricity demanded by the user, making it closer to the production curve of a CHP reciprocating engine. In particular, instead of relying on electrical chillers, the cooling demand can be covered by exploiting the available waste heat of the engine in an absorption refrigeration cycle, thus decreasing the electrical demand.

This modification of the cogeneration system into a trigeneration one is highly beneficial, since it allows exploiting almost all the heat produced by the prime mover throughout the year, increasing the first principal efficiency (or total efficiency) of the plant as well as decreasing the primary energy consumption vs. conventional solutions, NG boiler and electric grid.

II.4.1 Proposed design

The absorption refrigerator can theoretically replace the existing compression groups, producing the nominal cooling power (348 kW). On the other hand, it should be taken into account that the addition of the absorption cycle reduces the electricity required by the site and consequently the heat produced by the cogenerative engine, at least in a scenario where the design criteria of the cogenerator is to minimize (or even prevent) the exchange of electricity with the grid. Therefore, the size of the refrigerator must be chosen in order to minimize the waste of thermal energy but at the same time the engine should be able to provide the totality of required heat (apart from possible integration with conventional boilers, always available for backup, which is however required).

Taking into account the two phenomena and considering a Coefficient of Performance (COP) equal to 0.7 for a single-effect Li- Br absorption chiller, it has been determined that the optimal size of the absorption machine is around 150 and 180 kW of cooling power.

According to the simplified scheme presented , the absorption chiller is fed with the hot water circuit of 90 °C produced by the reciprocating engines, the same feeding the other thermal users of the system. The cooling power is generally produced by the absorption refrigerator, while the conventional compression chillers operate only when it is necessary to integrate the missing cooling capacity (in summer). (Paolo Silva, 2018)

II-5 Integrating the Trigeneration system

The CCHP system consists of a power generation unit (PGU), a waste recovery system, a back-up boiler, cooling system and heating system, which is shown in the figure II.3. Here the cooling system adopts the combination of electric chiller and absorption chiller because the excess electricity may be usually produced by CCHP system following thermal demand and the excess electricity is not allowed to be sold back to grid. The CCHP system operates following thermal demand, which is a common and simple operation strategy (Cardona E, 2003).

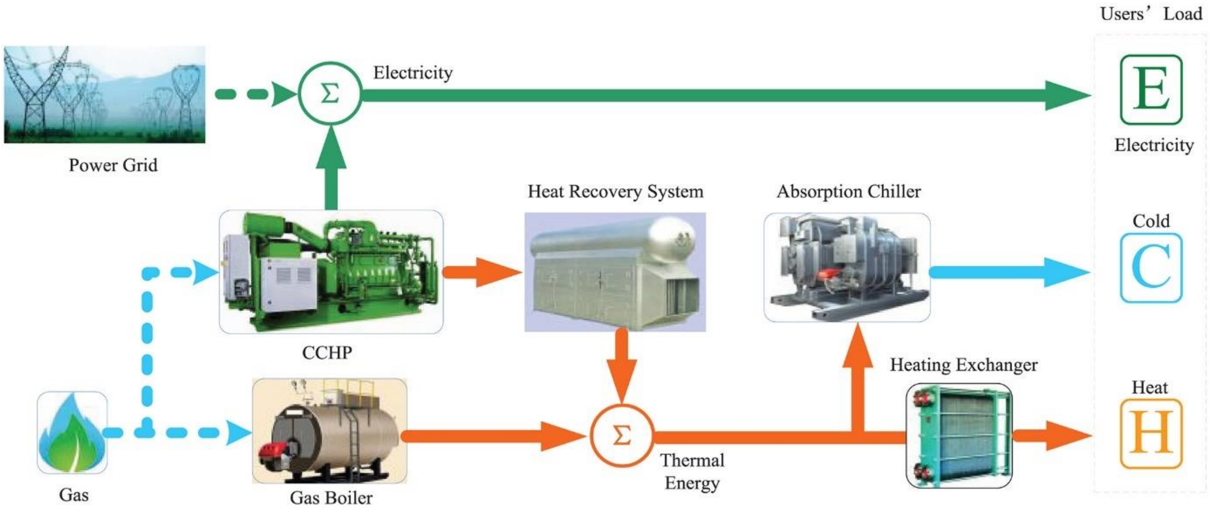


Figure II 3:Current Base-Case process flow configuration of the compressor station

The PGU is driven by natural gas and produces the electricity to building. The high-temperature exhaust gas of PGU is recovered to accommodate the thermal load for cooling in summer and heating in winter. If the heating does not completely satisfy the application needs, a supplementary boiler can be used. Similarly, when the amount of generated electricity by PGU is not enough, the additional electricity comes from the local grid. On the contrary, when there are excess heat or electricity produced by CCHP system, the excess energy products are dissipated from CCHP system. Consequently, the operation of PGU must reduce the excess products when it satisfy one energy demand of building. The balance of the electric energy in CCHP system is expressed (Jiang-Jiang Wang*, 2009)

II-5-1 The standard system (gas turbine)

The objective of this internship is to estimate the efficiency of the PGT25 (GE) turbine, and to integrate a combined cycle cogeneration system within the old one. The cycle used in the calculation is Brayton-joule cycle with the natural gas as fuel:

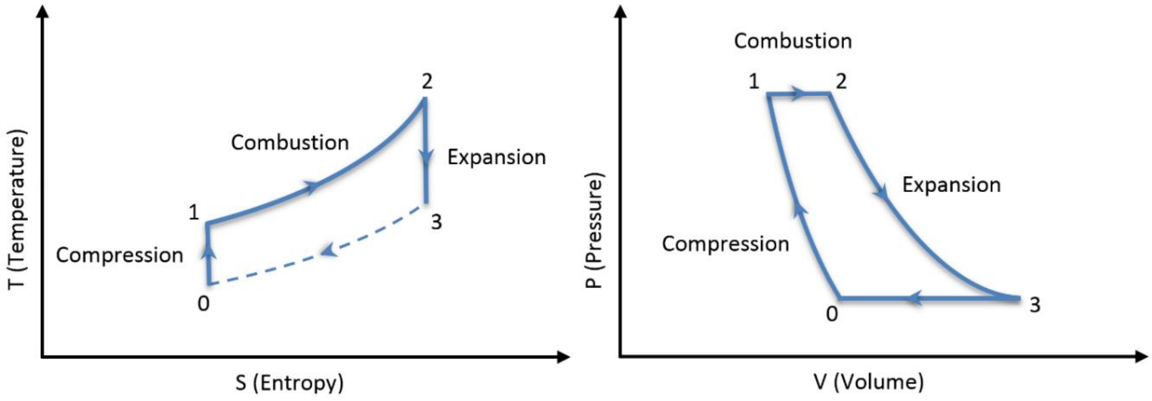


Figure II 4:Baryton-Joule Cycle

II-5-1.1 The calculation processes

First, we start by defining the gas turbine efficiency equation:

$$\eta_{GT} = \frac{W_{output}}{W_{input}} \quad (2\text{-}1)$$

With:

- **W_{output}**: The power generated by the turbine section.
- **W_{input}**: The power supplied to the combustion chamber.

So, we calculate the power extracted from the turbine section and the power supplied to the combustion chamber.

- Turbine generated power:

The extracted power is the intermission power on the turbine, the blades of the turbine absorb the burnt and hot gas energy by transforming it into kinetic energy in a form of rotational movement, thus the equation used to calculate this power can be expressed like this:

$$W_{output} = W_{Turbine} = \dot{m}_g \times Cp_g \times (T_3 - T_5) \text{ ......(2-2)}$$

- **$\dot{m}_g$:** the mass flow rate of exhaust gas. (kg/s)
- **Cp_g:** Specific heat of exhaust gas = 1.22 kJ / kg. °C.
- **T_3:** The combustion temperature (the maximum temperature) = 646 °C.
- **T_5:** The exhaust gas temperature = 525 °C.

First, we must calculate the exhaust gas flow exiting the gas turbine:

$$\dot{m}_g = \dot{m}_f + \dot{m}_{air} \text{ ....(2.3)}$$

- **$\dot{m}_f$:** the mass flow rate of fuel (Natural gas).
- **$\dot{m}_{air}$:** mass flow rate of the intake air.

The value of **$\dot{m}_f$** is the total mass flow rate of the fuel consumed by the gas turbine, it was obtained from the station control room, along with other information in the period of February 2015 were obtained:

- The turbine is TC2(turbo-compressor number 2) with a speed of 88%.
- Total operating hours: 629 h (in February).
- Fuel consumption: 1,790,400 m^3.
- The combustion temperature T_3 = 646 °C.

- The density of Natural gas ϱ= 0.845 kg / m^3 (Base, 2015)

To facilitate the calculation, natural gas is treated like perfect methane and under standard conditions.

The general methane combustion equation:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{(2.4)}$$

We start by converting the value of the fuel flow rate to kg/s:

$$\dot{m}_f = F_c \times \varrho/(\mathrm{h} \times 3600)$$

$$\dot{m}_f = 0.6752\ kg/s.$$

we balance the equation with the given quantity:

$$0.675CH_4 + 2(0.675)O_2 \rightarrow 0.675CO_2 + 1.35H_2O$$

We have the percentage of O_2 in the air is **20.8%** thus, for a 100% of air we multiply the equation by 5, and then by 10 (the assumed core cooling air).

$$\dot{m}_{air} = m_{CO_2} \times 2 \times 5 \times 10 = 67.5\ kg/s.$$

So, the exhaust gas flow is:

$$\dot{m}_g = \dot{m}_f + \dot{m}_{air} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.5)$$

$$\dot{m}_g = 68.17\ kg/s.$$

The value calculated is approximately the same one given by the manufacturer (GE) for the same gas turbine, and it was confirmed by the station engineer.

We can deduce the extracted power:

$$W_{output} = \dot{m}_g \dot{\times} c_p \times (T_3 - T_5)$$

$$W_{output} = 10063.25\ KW.$$

- The power supplied to the turbine:

$$W_{intput} = \dot{m}_f \times PCI \text{ ....}\textbf{(2.6)}$$

With:

- PCI: Lower calorific value power; PCI =44.45 MJ/kg (Base, 2015)

$$W_{intput} = 30.01264\ KW.$$

Finally, the efficiency of the turbine is:

$$\boldsymbol{\eta}_{\mathrm{GT}} = 10063.25/30705.75 = 0.327$$

$$\boldsymbol{\eta}_{\mathrm{GT}} = 32\%.$$

when comparing the resulted efficiency to the manufacturer efficiency (**36%**) we see a decrease in the performance of the turbine this is due to long period servicing and the mechanical wear.

II.5.2 Reference system (combined cycle)

The recovery of heat from the exhaust gases of the gas turbines of the Berkaoui compressor station by the transformation of the open cycle (GT) into an optimal cogeneration system of the gas-vapor combined cycle type is necessary in order to minimize consumption. energy and reduce CO_2 emissions. For this we have adopted the following reference electrical system:

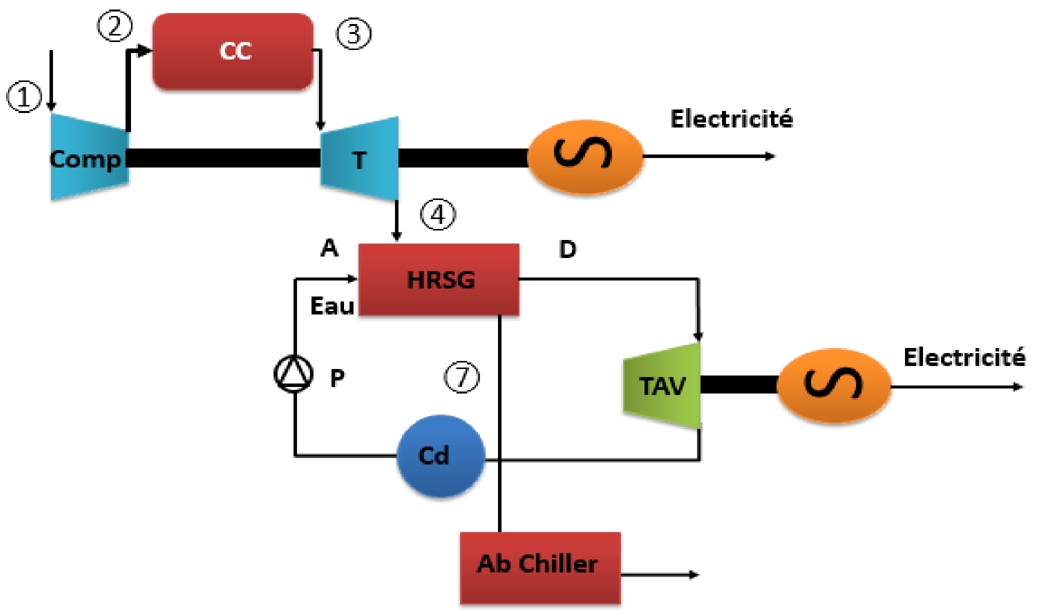


Figure II 5: Reference cogeneration system (combined cycle)

The gas turbine exhaust gases are at a relatively high temperature (around 525 ° C). The corresponding sensible enthalpy constitutes a sufficient heat source to feed the boiler of a Rankine cycle. The resulting combined cycle makes it possible to enhance the advantages of each of the two cycles in order to increase the resulting power.

The reference system consists of standard system (gas turbine) of the station, in addition the next components are required, the recovery boiler (HRSG), the steam turbine (ST) and the condenser. The combined cycle efficiency equation is:

$$\eta_{CC} = \frac{W_{gt}+W_{st}-W_p}{\dot{m}_f \times PCI} \text{..............................} \textbf{(2.7)}$$

II.5.3 Energetic study of the combined cycle (GT-ST)

To study the possibilities of implementing cogeneration (combined cycle) in the station, it is necessary to know the classes of temperature, power, efficiency, in each stage of the system.

II.5.3.1 Gas turbine

The gas turbine to be used in the reference system is the same gas turbine used in the station, the characteristics and the calculation of this gas turbine are calculated in the standard system, the results are presented in the next table:

Table II 1:standard system (gas turbine) results

Exhaust mass flow rate $\dot{m}_g$ (kg/s)	**Output power W_{output} (kW)**	**Input power W_{input} (kW)**	**Efficiency η_{GT} (%)**
68.17	10063.25	30.01264	32

II.5.3.2 Recovery boiler (HSRG)

A heat recovery steam generator (HRSG) is a type of heat exchanger between hot gases stream out from gas turbine plant and demineralized water to produce high pressure and temperature steam to drive a steam turbine and generate electricity (combined cycle). Waste heat could obviously be a very desirable energy source since the HRSG is available at almost zero operating cost and reduces emissions to the environment. HRSG increases the efficiency of the gas turbine Brayton cycle. For example, normal gas turbine efficiency in open cycle mode is as low as 35–40%. This efficiency can be raised by adding another cycle (Rankine cycle) to increase the cycle efficiency up to 50%. (Asmar, 2018).

The HRSG is composed of several heat exchangers making it a large heat exchanger. The heat exchanger tubes are set in different modules or sections, popularly known as: Economizer, Evaporator, Super-Heater, as illustrated in figII.9.

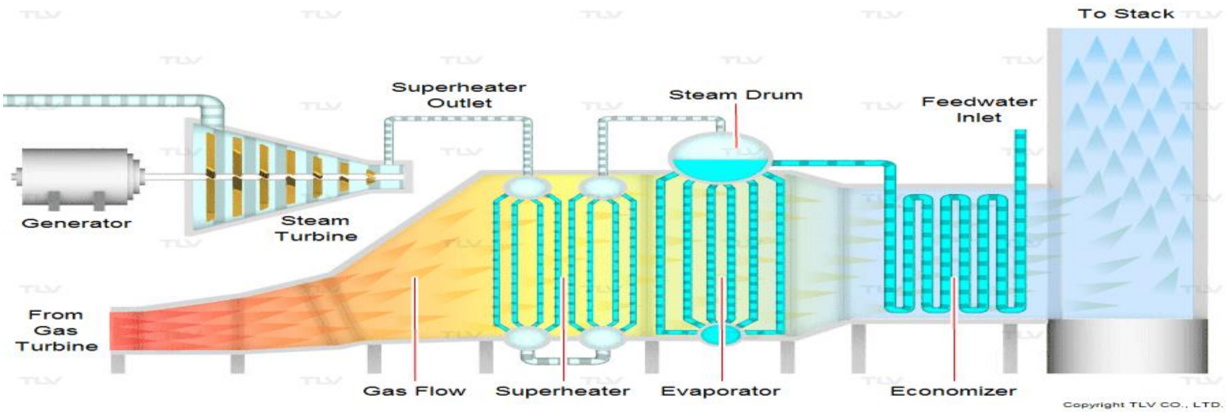


Figure II 6:HRSG flow diagram. (Company, 2019)

The heat transfer between the hot exhaust gas (outside the tubes) and the water/steam (inside the tubes) can be summarized by the following formula:

$$Q = \int_{T_{inlet}}^{T_{outlet}} \dot{m}_g \times Cp_g \times (T)dT = \dot{m}_s \Delta h \text{ ....}\mathbf{(2.8)}$$

$$Q = (U \times A) \times \Delta TLM \text{ ....}\mathbf{(2.9)}$$

Where:

- **Cp_{gas}** :the specific heat of the exhaust gases (kJ / kg. K).
- $\dot{m}_s$**:** steam mass flow rate (kg/s).
- **Δh:** enthalpy difference of the steam (kJ/kg).
- **U** :is the overall heat transfer coefficient (W/m^2-K).
- **A:** is the heat transfer surface area (m^2) .
- **ΔTLM:** is the log mean temperature difference defined as:

$$\Delta TLM = \frac{\Delta T_A - \Delta T_B}{ln\left[\frac{\Delta T_A}{\Delta T_B}\right]} \text{ ....}\mathbf{(2.10)}$$

- ΔT_A :is the temperature difference between hot gas entering the “tube bank” and heated steam or water exiting it.

- ΔT_B :is the temperature difference between the hot gas exiting the tube bank and steam or water entering it (Gülen, 2020).

II.5.3.3 Steam turbine

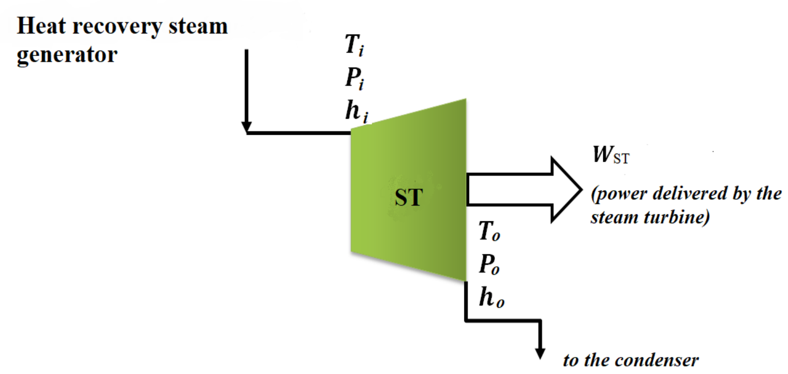


Figure II 7:The steam flow throughout the ST

1) The enthalpy at the inlet of the steam turbine (h_{in}):

For the steam turbine we need to find the enthalpy (h_o) of the outlet we consider pressure losses and losses between the boiler and the steam turbine inlet, the pressure at the inlet of the steam turbine will be equal to (V.E. Cenusa, 2006):

$$P_i = P_D \times 0.9 \quad \textbf{(2.11)}$$

$P_i = 4.24 \times 0.9$

$P_i = 3.816$ MPa

P_i **= 38.16 bar**

-The temperature at the inlet of the steam turbine will be equal to: T_i **= 395 °C.**

Using the thermodynamic tables to find that the enthalpy and entropy at the inlet the steam turbine.

The isentropic efficiency of the steam turbine: $\eta_{is} = \mathbf{0.8}$.

To calculate h_0 you need to determine the pressure at the condenser, to start this pressure is between 5 and 10 kPa (De, 2020)

2) Calculation of the steam turbine outlet enthalpy:

For a given pressure and from the thermodynamic tables on tires the data following:

h_f: Enthalpy of water in the saturated liquid state.

Δh_{fg} : Difference between the enthalpy of water in the saturated vapor state and in the saturated liquid state

S_f : Entropy of water in the saturated liquid state

ΔS_{fg} : Difference between the enthalpy of water in the saturated vapor state and in the saturated liquid state.

3) Calculation of the isentropic fraction:

$$X_{is} = \frac{S_{is}-S_f}{\Delta S_{fg}} \quad \textbf{(2.12)}$$

$$X_{is} = \frac{h_{is}-h_f}{\Delta h_{fg}} \quad \textbf{(2.13)}$$

We can determine h_{is}: $h_{is} = (X_{is} \times \Delta h_{fg}) + h_f$

Using the isentropic efficiency of the steam turbine, we obtain:

$$\eta_{STis} = \frac{h_i-h_0}{h_i-h_{is}} \quad \textbf{(2.14)}$$

$$h_0 = h_i - (h_i - h_{is}) \times \eta_{STis} \quad \textbf{(2.15)}$$

Calculate the real fraction:

$$X = \frac{ho - hf}{\Delta h_{fg}} \quad \textbf{(2.16)}$$

Calculation of power that can be supplied by the steam turbine:

$$W_{ST} = \dot{m}_S \times (h_i - h_0) \text{……………………………………………}\mathbf{(2.17)}$$

II.5.3.4 Condenser and preheater

The condenser is a counterflow heat exchanger attached to the exhaust of the steam turbine, it receives saturated steam and then condense the steam by releasing its heat with the cold water so the saturated steam can be transformed to water in order to pump it to the preheater, furthermore the water entre the preheater to rise its temperature before the HRSG.

II.5.4 Consumption of gas to the production of electricity

Energy demand is calculated on the basis of specific consumption per product. It is equal to the sum of the specific consumption of each fuel multiplied by the production of each type of product (Recioui, 2017). Natural gas is the most used fuel for the production of electricity in Algeria, covering almost 97% of demand. our hypothesis is based on an average annual working time of the turbo-compressor with 7920 hours (11 months / 24 h) of operation time.

$$TC_{NG} = SC_{NG} \times E_{gener} \text{……………………………………………}\mathbf{(2.18)}$$

TC_{NG} : Total Consumption of natural gas in one year (m^3).

SC_{NG}: Specific Consumption of natural gas (m^3/kWh), represent the consumption by production unit.

E_{gener} : Energy generated by gas turbine (kWh).

$$E_{gener} = 79.7 MWh.$$

$$TC_{NG} = 21.52\ Mm^3. \text{ (Standard system)}$$

In our study, the value of the specific consumption of the gas used is the average of the values between 1980 and 2013. It is considered to be constant during the simulated years (from 2015 to 2045). It is equal to 0.270 m^3 / kWh (865.3 m^3 / Mtoe) (Recioui, 2017).

II.5.5 cooling and heating

For a fixed electric cooling to cool load ratio CCHP system, electric load, cooling load and heating load can only match at a point. However, by introducing the variational electric cooling to cool load ratio, the range for the energy loads to match with each other can be extended. By adjusting the electric cooling to cool load ratio, the electric load and thermal load can be accordingly tuned. Since x can only vary in [0, 1], This range can be obtained by two limiting situations. (2012)

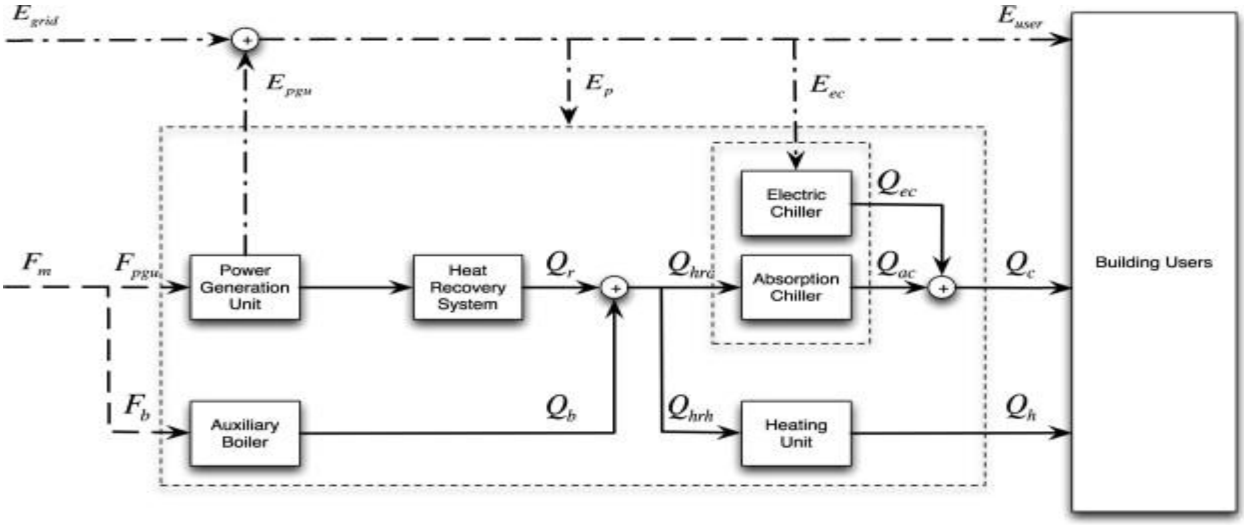


Figure II 8:The CCHP system with hybrid chillers implemented (2012)

First, when x = 0, the absorption chiller takes all the cooling
load. Thus, we have Q_{ac} =Q_c
And

$$Q_{hrc} = \frac{Q_{ac}}{COP_{ac}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{(2.19)}$$

Where COP$_{ac}$ is the absorption chiller’s COP. At the heating unit node, we have

$$Q_{hrh} = \frac{Q_h}{\eta_h} \text{...} \mathbf{(2.20)}$$

Where η_h is the heating efficiency of the heating unit. Then it can be readily derived as

$$Q_r = Q_{hrc} + Q_{hrh} = \frac{Q_{as}}{COP_{as}} + \frac{Q_h}{\eta_h} \text{...} \mathbf{(2.21)}$$

In the next step, x is set to be 1, implying that the electric chiller takes all the cooling load and the absorption chiller is left idle.

Hence

$$Q_r = \frac{Q_h}{\eta_h} \text{...} \mathbf{(2.22)}$$

II.5.6 CO_2 emissions analysis

Calculating the carbon content of electricity is an important issue for evaluating actions in the fight against climate change. In general, Carbon dioxide emissions are estimated based on fuel consumption. Emissions are directly proportional to the fuel consumption (Recioui, 2017). The quantity of carbon dioxide, Q_{CO_2}, is that emitted during the production of electricity at the power stations. This amount is determined based on the amount of electricity produced. In our study, it is calculated according to the following relation:

$$Q_{CO_2} = E \,.\, F_{emission} \text{...} \mathbf{(2.23)}$$

Where:

E : Electricity (kWh).

F_{emission} : Emission Factor (kg CO_2 equivalent /kWh).

The imperatives of preserving the environment require the use of natural gas as primary energy to produce electricity, compared to other fossil fuels considered to be polluting, knowing that the gas resource is widely available in Algeria. Combined cycle technology makes it possible to obtain savings in emissions due to the substitution of gas turbines (open cycle). The CO_2 gain can be written according to the relationship:

$$Avoided_{CO_2} = E_{Cogeneration}.F_{emission} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathbf{(2.24)}$$

Where:

$E_{Cogeneration}$: Electricity produced by cogeneration in kWh.

The use of this electricity emission factor in the modeling will make it possible to account for the impact in terms of the greenhouse effect of projects aimed at encouraging energy conservation actions. For the Algerian electricity sector, the emission factor is 548 g CO_2 per electric kWh in 2011 (IEA, 2013). In our study, we will therefore consider this value to be an average value.

$$E_{cogeneration} = 57.95MWh.$$

$$TC_{NG} = 15.646Mm^3\text{(saved primary energy)}.$$

To produce this energy quantity with cogeneration we saved 15.81Gm^3 of primary energy.

$$Avoided_{CO_2} = 31.7kt$$

By integrating the cogeneration, we can save a 32 kt quantity of Co2 annually.

II-6 Results and discussion

The feasibility calculation for the transformation into a combined cycle system is described in detail in Annex. It covers the entire installation: the recovery boiler, the steam turbine and the condenser.

The results obtained from the calculation process and by using Microsoft EXCEL are presented in tableII.2, the results are related to the HRSG unit and the condenser and the preheater which are heat exchangers.

Table II 2:Calculated values of the heat exchangers in the system

	Economizer	Evaporator	Superheater	Condenser	Preheater
ΔTLM (°K)	306.34	341.01	441.79	281.48	**364.24**
Heat transfer Q (kW)	7067.79	17493.53	4225.63	19589.97	**2342.24**
Exchange area A (m^2)	**54.15**	**117.65**	**19.12**	**23.19**	**12.86**

The next table contains the power generated by the steam turbine and the mass flow rate of the steam flowing in it, also the efficiency of the reference combined cycle:

Table II 3::the reference system results

Steam turbine		Combined cycle
Steam mass flow rate $\dot{m}_s$ (kg/s)	**Generated power W_{ST} (MW)**	Efficiency η_{st} (%)
10.3137	**7.317**	**43.7**

We can see an increase in the efficiency compared to the standard system of the station, this improvement is due to the waste heat recovering, this heat is used to generate electrical power of magnitude 7.317 MW_{elec} by using a steam turbine. The results of the cooling and heating analysis section are presents in the following table:

Table II 4::The results of of the cooling and heating

thermal energy recovered Q_r (Kj)	thermal energy cooling Q_c (Kj) x=0	thermal energy heating Q_h (Kj) x=1
38705.76455	27094.04	30964.61

The results of the CO_2 analysis section are presents in the following table:

Table II 5::The results of CO2 emission analysis section

Primary energy saved (Mm^3)	CO$_2$ emission saved (kt)	Energy gained (GWh)
15.64	**31.7**	**57.95**

According to the table, the cogeneration system improves efficiency, which goes from 32% in the simple and open gas cycle to 43.7% in the combined cycle, as well as an energy gain of 57.95 MWh, which reflects a natural gas saving of 15.64 Mm^3 and a reduction of 31.7 kt of CO$_2$.

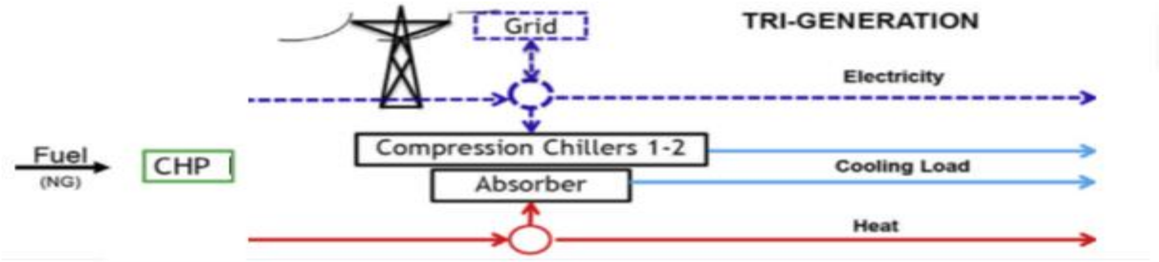


Figure II 9:Flow diagram of the proposed trigenerative solution with three reciprocating

We introduced this system in the stations in order to provide heating, cooling and electricity for the residences

II-7 Conclusion

Thanks to the studies that we have carried out in the pressure stations that rely on gas turbines in Configure a real mechanical drive replenishment, regarding the quantity Gases have the same requirements as electricity.

Beside The amount of natural gas for heating and operating gas turbines There are cooling loads, for gas processing, and office buildings Data center as well as electrical loads for office buildings and turbines helpers. The solution depends on the configuration with Combined multi-reciprocating internal combustion engines Cooling, heat and power units (CCHP).

Chapter III: Economic Analysis of CCHP System

III-1-Introduction

Gas and electricity are very energy efficient, and both require tens of billions of dollars to spend on peak demand (Bofeng Yan1, 2016). The gas powered CCHP system is an effective solution for improving energy efficiency. Combining cooling, heating, and power generation (trigeneration) (Paolo Silva, 2018), which is called CCHP for short, and as a result we get in the analysis energy efficiency, total energy product, efficiency, and total product cost per unit. Peng et al. As it can effectively solve the seasonal electricity and gas shortages, as well as reduce the demand for new generation capacity, investments in transmission and distribution infrastructure, and related investments in gas due to the final consumption of energy (Bofeng Yan1, 2016). In addition, gas-fired CCHP systems can also improve living environments and reduce pollutant emissions. But the currently distributed power grid production is limited and gas prices are increasing.

Under this situation, can the advantages of high energy efficiency of a distributed power system be translated into significant economic benefit? Meaning, can distributed energy systems be profitable? What is the level of these profits? Many doubts remained. This chapter performs an economic analysis of distributed energy investments in the world by examining the factors that affect the economics of gas-fired CCHP programs (2023) that proposed a CCHP system model with turbines, and the results showed that CCHP is a more demanding system.

III-2-Economic analysis of a CCHP energy supply system

Trigeneration distributed energy system investments require a comprehensive analysis. From the enterprises’ economic benefits, enterprises should gain the energy saving efficiency as well as the necessary investment revenue. This section will perform an analysis from the aspect of system operation costs, operation incomes and related financial indicators.

III- 2-1 Cost analysis of a CCHP system

III-2-1-1 Initial investment l_0

The main investments for CCHP systems are the gas turbine systems, absorption chillers and heat boilers. The price of a gas turbine generally includes the control system and gas/diesel dual fuel system. Electricity generated by gas turbines can be directly connected to a 380 V power supply system and the frequency and peak can be adjusted. Control systems can be matched to the gas turbine and automated.

$$l_0 = 8809668\, USD$$

Table III 1::investment cost of the system (Zhonghui Liu 1, 2021)

Equipment	Investment cost (USD/kWh)
Gas engine	750
Heat recover unit	130
Heat exchanger	31
Absorption chiller	154
Electric chiller	108
Boiler	31

The construction competition period for each distributed systems is one year, while the period for a large gas-steam cycle system is about three years, corresponding to the actual situation. During the investment budget procession, in each system, the production, repayment, depreciation and amortization periods should be the same so that comparability among all of the systems is maintained.

III-2-1-2-Operation cost C_{fm}

After a trigeneration system is put into operation, the costs are generally for operation and maintenance, fuel, and so on. When a project is completed, the first two costs are considered to be unchangeable factors, or fixed costs. In general, the construction investment of a gas turbine cycle system is low, with a high degree of automation and low-labor capacity. Thus, compared with conventional coal-fired power plants, this system has a smaller proportion of fixed costs, typically 35%-55%. As seen from the system configuration, among the fuels consumed by the systems, gas accounts for the largest proportion.

In addition to the fuel used for the gas turbine, flue gases of direct-fired machines and waste heat boiler combustion also requires a large amount of fuel, so the cost of burning gas is the largest, reaching up to 45%-65%. For simplicity, the calculation models only consider the amount of gas consumed by a device, but not the total consumption during the operation process; because fuel costs are the largest, the operation of a system will depend on the gas price to a large extent. The operation costs of trigeneration systems mainly involve the annual fuel cost (C_{fu}) and operation and the steps of a sensitivity analysis are as follows:

(1) - Choose uncertainties that are necessary to analysis and set the range of variation of these factors. There are two principals for selecting factors: changes in the factors will strongly affect the economic indicators in the possible scope of changes, the accuracy of the factors' data is unclear.

(2) - Perform the certainty analysis. Sensitivity analysis is based on a certain economic analysis. Generally speaking, the indicator of the sensitivity analysis should be consistent with the indicator of the certainty analysis and not exceed the scope of the certainty analysis maintenance costs (C_{am}).

$$C_{fm} = C_{fu} + C_{am} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{\textit{(3.1)}}$$

C_{am}: analysis maintenance costs $= 275192.37\ USD$

Table III 2::maintenance cost of the system (Zhonghui Liu 1, 2021)

Equipment	Maintenance cost (USD/kW/year)
Gas engine	30
Heat recover unit	5,2
Heat exchanger	0.05
Absorption chiller	1.24
Electric chiller	1.05
Boiler	0.07

$$C_{fu} = \frac{3600 \times W \times H \times P_f}{\eta_e \times \delta_1} \text{..............................} \mathbf{(3.2)}$$

Where:

-***W:*** is the generation power =7317 kW

- ***H:*** is the annual hours of operation of the equipment=8760 h

- ***pf:*** is the fuel price =0.76 USD/m^3 (globalpetrolprices.com, 2023)

- **η:** *e* is generation efficiency =44 %

-***δ1:*** is the fuel calorific value =37560 kJ/m^3.

III-2-2 Analysis of system revenue

For CCHP energy supply systems, there are two types of economic revenues (R_{al}, USD) after the system is put into operation: electricity revenues (R_e, USD) and cooling and heating revenues ($R_c$and R_h, USD).

$$R_{al} = R_e + R_h + R_c \text{.........................} \mathbf{(3.3)}$$

First, the first return on project investment is the return on electricity. Commercial and industrial electricity Prices are complicated in Algeria. We use average prices to calculate convenience, and we can also use the weighted value of the local tariff rate. In the calculation process, the power generation efficiency of the device should be It is taken into account according to the local average, and other attenuation factors do not need to be It is considered.

$$R_e = W \times H \times P_e = G \times P_e \text{.......................} \mathbf{(3.4)}$$

Where:

-G : the generation capacity =64096920 kWh

-pe: is the electricity price =0.19 USD/kWh. (globalpetrolprices.com, 2023)

The second revenue of a project investment is cooling and heating revenue. To compare each system easily, we can take the maximum cost of production cooling and heating in a system as a reference price. For example, the calorific value calculation method considers the thermal efficiency after the waste heat boiler combustion, which is on the basis of gas price. Simultaneously, we also need to pay water charges.

$$R_h = \frac{Q_h \times d \times 24 \times 3600 \times P_h}{10^6} \text{................................} \mathbf{(3.5)}$$

$$R_c = \frac{Q_c \times d \times 24 \times 3600 \times P_c}{10^6} \text{..........................} \mathbf{(3.6)}$$

Where :

-Q_h: the heating supplies= 8.60 kW

-Q_c: the cooling supplies = 7.52 kW

-***d:*** is the annual supply= 365 day

-p_h**:** the price of heating= 0.25 USD/GJ (WEFORUM.ORG, 2022)

-p_c: the price of cooling = 0.25 USD/GJ.

III-2-3 Financial indicators of economic evaluations

Economic effects are the core of investment project evaluations. The variety of economic effect evaluation indicators reflect the different views of project economics. Combining the need of economic evaluation of a CCHP system, this section selects three main indicators: investment payback period, net present value and internal rate of return for economic analysis.

III-2-3-1-Net present value *NPV*

NPV refers to the balance between the present value of total income and the initial investment.

$$NPV = \sum_{t=1}^{n} \frac{F_t}{(1+i_0)} - l_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(3.7)}$$

Where, F_t is the cash flow in year t in USD, i_0 is the discount rate in % and $l_0$is the initial investment in USD.

III-2-3-2-Payback period

(i) Static investment payback period T_j does not consider the time value.

$$T_j = \frac{l_0}{A_t} \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(3.8)}$$

$$A_t = R_{al} + C_{fm} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{\mathit{(3.9)}}$$

Where:

- $\boldsymbol{A_t}$ **:** annual net income =1850390.9 USD.

(ii) Dynamic investment payback period T_D considers the time value and is the time when cumulative NPV is equal to zero.

$$T_D = [T_D - 1] + \frac{|NPV_{[T_D-1]}|}{A_{[T_D]}} \text{..................}\mathbf{(3.10)}$$

Where:

-$[\boldsymbol{T_D} - \mathbf{1}]$:is the last year in which cumulative NPV is negative (in the year T_D, cumulative net present value is greater than zero).

-$|NPV_{[T_D-1]}|$: is the absolute value of NPV until the year$[T_D - 1]A_{[T_D]}$ is net income in the year $[T_D]$.

III-2-3-3 Internal rate of return *IRR*

Internal rate of return rate calculated when the annual net cash flow equals zero during the entire calculation period. The internal rate of return reflects the project's resilience to investment spending; the higher the value is, the better the economy of the project. When the internal rate of return is bigger than the benchmark rate of return, the project is acceptable. It is an important financial indicator for the evaluation of investment projects.

$$\sum_{t=0}^{n} A_t(1 + IRR)^{-t} = 0 \text{.................}\mathbf{(3.11)}$$

III-3Factors affecting the project economy and sensitivity analysis

To improve the reliability of economic analysis and scientific decision-making during the technical and economic evaluation of the project, we need to further analysis the impact of the uncertainty factors on the project economic indicators on the basis of the certainty analysis, to predict the possible risks after the implementation of a project.

III-3-1-Factors affecting the project economy

During operation, due to the impact of fuel, heating and electricity prices, the annual system utilization hours and other factors, the technical and economic data of a trigeneration system may change drastically in a dynamic environment.

This section selects fuel prices, heating prices, electricity prices and annual heating days as the variables and makes an analysis of the project economy.

III-3-1-1-Fuel price effects

Fuel costs make up a large proportion in the DES/CCHP system's operation costs, up to 78%, with a minimum of only 44%. Therefore, fluctuations in the gas price will directly affect the annual operation costs of the system.

III-3-1-2-Heating and electricity price effects

Raising the heating and electricity price will increase investment incomes and improve the operation economy of the system. The higher the generation efficiency, the bigger the proportion that the powers supply makes up in the annual incomes. Therefore, the effect of electricity price is more than heating price effects.

III-3-1-3-Annual heating day effects

The longer the heating period, the higher the heating load and system energy utilization efficiency. This is the advantage of DES/CCHP systems. If only the heating load is adequate, the system can gain a considerable heating income.

III-4- Empirical studies in typical trigeneration projects

Trigeneration" project The Algeria Gas Group Control Center building is used as an example. Project Time Demand Electricity and Heating at Work... Here we explain how to determine the ultimate Gas Fired CCHP investment plan at Work at Work. First, the investment scheme, actual energy use requests, etc., the final investment plan will be determined by technical and economic analysis among these programs. This section outlines the experiment conducted by the University of Energy to study the economic efficiency of distributed trigeneration and to analyze the impact of the distributed system on the economic efficiency of grid enterprises when they participate in investing in the system.

III-5 Results and discussion

The results of the costs and revenue are presents in the following table:

Table III 3::results of the costs of the system and system revenue

The costs of the system (USD)	
C_{fu}	**10052958.7 USD**
C_{ma}	**275192.37 USD**
C_{fm}	**10328151.1 USD**
Analysis of system revenue	
R_e	**12178414.8 USD**
R_h	**67.80 USD**
R_c	**59.37 USD**
R_{al}	**12178542 USD**

The results of Economic evaluation financial indicators are presents in the following table:

Table III 4::results of economic evaluations financial indicators

Economic evaluation financial indicators	
NPV (USD)	**582346,4**
A_t(USD)	**1850390.9**
T_D (Year)	**5.43**
IRR (%)	**17**

The energy and economic balances obtained from the yearly simulation with the reference weeks are shown in Table 3. Average first-law efficiency is near to the nominal efficiency of the engines, and the primary energy saving, calculated according to EU directives , is 17%. The yearly cash flow is about 1850390.9 USD and the economic parameters show that the investment can be

III-6 Conclusions

In this study, the combination of cooling, heating and power (CCHP) thermodynamic system and thermos is economically efficient. Integration of heating and cooling units in a gas fired power plant.

CCHP gas combustion system is good for both customers and beneficial at present, the improvement is to reduce the unit cost of electricity, heating and cooling, increase power and energy efficiency. Thermodynamics, distributed energy investment mode is gradually shifting to maintenance and construction investors and outside energy company investors participate in energy efficiency participation. It should be noted that investors must sign the contract for the establishment of a distributed energy supply system and clarify the rights and obligations for the process of establishing and operating the entire system, especially the energy clarification, and the percentage of efficiency that investors can share when operating the system is 582346,4 USD. The returns of a gas-fired CCHP system are greatly affected by the price of fuel and the price of electricity.

During the operation process, the operating costs of the third-generation system after 5 years are mainly fuel costs and operation and maintenance costs, and fuel costs have greater market uncertainty in the future. We can see for example, changes in the price of fuel are bound to affect the payback period of the project, and changes in the price of electricity will also affect the payback period due to changes in revenue. In order to avoid this possible to accept or reduce the impact of risks in the future, we need to make accurate fuel and electricity price predictions before making investment decisions. A reasonable share of energy efficiency will help recover the investment in gas fired CCHP. Where a third party, such as energy service companies, is involved in the distributed construction process, energy projects, revenue primarily comes from energy efficiency participation in the gas-fired CCHP. Therefore, our energy efficiency share ratio is determined according to specific projects to ensure that it wins reasonably.

General Conclusion

General Conclusion

The present work deals with a feasibility study for an increase capacity and energy efficiency of a compressor station, where there was an innovative implementation of the three-generation scheme Proposal. The compressor station is based on a gas turbine Mechanical drive configuration and real time data are available before regeneration, with respect to the amount of compression and consumed gas as well as electricity requirements. Besides The amount of natural gas for heating and operating gas turbines There are cooling loads, for gas processing, and office buildings Data center as well as electrical loads for office buildings and turbines helpers. The proposed solution depends on the configuration with Combined multi-reciprocating steam turbines Cooling, Heat, and Power (CCHP) units, in order to increase system flexibility and reliability, in which there is a single absorption chiller Two existing pressure coolers are added to the disposable tap heat from the motors.

The proposed triple solution demonstrates its feasibility Economical (internal rate of return 17%) and able to obtain Primary Energy Saving (PES) of about 29%, which leads to a similar achievement Also reduced in terms of carbon dioxide emissions. Consider the strategy The importance of compressor stations, is playing an increasing importance Role from the point of view of the energy infrastructure network and Integration of the gas network with the approved electrical network Configuration can be seen as a solution to increase reliability. In reality, The actuators allow the system to operate in an off-grid mode in case Power outages, provided they are adequately sized and controlled As in the proposed plant scheme

References

References

(CERC) Central Electricity Regulatory Commission www.cercind.gov.in [Journal]. - [s.l.] : http://www.cercind.gov.in, 2014.

A new operation strategy for CCHP systems with hybrid chillers [Journal]. - 2012.

A new operation strategy for CCHP systems with hybrid chillers [Journal]. - 2012.

Asmar J. Al. système électrique au Liban Thèse de Doctorat au système électrique au Liban [Journal]. - 2018.

Base D. D. E Sonatrach spa [Journal]. - 2015.

Bischi A Campanari S, Castiglioni AG, Manzolini G, Martelli E, Silva P Tri-generation systems optimization: comparison of heuristic and mixed integer linear programming approaches [Journal]. - Germany : https://doi.org/10.1115/GT2014-27028, 2014.

Bischi A Perez-Iribarren E, Campanari S, Manzolini G, Martelli E, Silva P, Cogeneration systems optimization: comparison of multi-step and mixed integer linear programming approaches. [Journal]. - [s.l.] : https://doi.org/10.1080/15435075.2016.1161635, 2016.

Bofeng Yan, Song Xue, Yuanfei Li, Jinhui Duan, Ming Zeng Gas-fired Combined Cooling, Heating and Power (CCHP) in Beijing: A Techno-economic Analysis [Journal]. - China : https://www.elsevier.com/open-access/userlicense/1.0/, 2016.

Cardona E Piacentino A A methodology for sizing a trigeneration plant in mediterranean areas [Journal]. - 2003.

CDU Koalitionsvertrag. [Journal]. - [s.l.] : www.cdu.de:http://www.cdu.de/sites/fdefault/files/media/dokumente/Koalitionsvertrag, 2013.

CODE. Cogeneration Observatory and Dissemination Europe [Journal]. - 2014.

Company TLV Waste Heat Recovery | TLV - A Steam Specialist Company (United Arab Emirates) [Journal]. - [s.l.] : https://www.tlv.com/global/ME/steam-theory/waste-heat-recovery.html, 2019.

De T., & L'ingénieur Convertisseurs thermiques, cycle à vapeur et combinée, cogénération [Journal]. - [s.l.] : https://www.techniques-ingenieur.fr/base-documentaire/energies-th4/conversion-et-transport-d-energie-42206210/convertisseurs-thermomecaniques-be8053/, 2020.

Energiewende Agora Report on the German Power System [Report]. - [s.l.] : https://www.agora-energiewende. de/ fileadmin / downloads / publikationen / Country Profiles / Agora_CP_Germany_web.pdf, 2015.

Factbook CIA - The World www.cia.gov [Journal]. - 2014.

globalpetrolprices.com [Online]. - https://ar.globalpetrolprices.com/lpg_prices/.

globalpetrolprices.com https://ar.globalpetrolprices.com/lpg_prices/ [Journal]. - 2023.

Gülen S. C. Gas Turbine Combined Cycle Power Plants [Journal]. - 2020.

IEA I. Production of Bio-methanol Technology Brief [Journal]. - [s.l.] : https://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP Tech Brief I08 Production_of_Bio-methanol.pdf, 2013.

ilyas Righi Sidahmed & Sahli The integration of a cogeneration system in a compressor station and the study of its effect on the electrical grid. Master desertation. - 2020.

Jiang-Jiang Wang* You-Yin Jing, Chun-Fa Zhang Optimization of capacity and operation for CCHP system by genetic algorithm [Journal]. - 2009.

Paolo Silva Aldo Bischi,Marco Lamberti,Stefano Campanari,Ennio Macchi,Danilo Tacchinardi Trigenerative solution for natural gas compressor stations: A north [Journal]. - Italian : [s.n.], 2018.

Project. Bricker [Online] // www.bricker-project.com. - http://www.bricker-project.com/Technologies/Chillers_thermally_activated_cooling_technologies.kl.

Pvt Bridge to India [Journal]. - [s.l.] : www.bridgetoindia.com, 2013.

Recioui B. Etude prospective de la récupération d ′ énergie en Algérie. 310. [Journal]. - 2017.

Solutions. Center for Climate and Energy www.c2es.org [Journal]. - [s.l.] : http://www.c2es.org/technology/factsheet/CogenerationCHP, 2014.

SONATRACH. CARTE DE RESEAU DE TRANSPORT DES HYDROCARBURES TRC 2013 [Journal] . 2013.

V.E. Cenusa M. Feidt, R. B. et A. B Optimisation des cycles combinés gaz – vapeur avec un ou deux niveaux de pression et chaudière à surface d'échange imposée. [Journal]. - 2006.

WEFORUM.ORG [Journal]. - 2022.

Zhonghui Liu , Weijun Gao, Fanyue Qian, Liting Zhang and Soichiro Kuroki. Potential Analysis and Optimization of Combined Cooling, Heating, and Power (CCHP) Systems for Eco-Campus Design Based on Comprehensive Performance Assessment [Journal]. - China : [s.n.], 2021.