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Review

Technology, optimization and decision-making review for cogeneration and trigeneration systems

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There is an increasing concern about the need for energy security and impact of greenhouse gas emission all over the world. Energy efficiency has been identified as part of the solution to ensure the energy supply as well as lower the greenhouse gas emissions. Combined Heating and Power generation (CHP) and Combined Cooling, Heating and Power generation (CCHP) systems can contribute to the reduction of primary energy consumption and greenhouse gas emissions in residential and tertiary sectors, by reducing fossil fuels demand and grid losses with respect to conventional systems. The trigeneration systems are characterized by very high energy efficiency (80 to 90%), as well as a less polluting aspect compared to the conventional energy production, since the waste heat is recovered from the engine cooling system and exhaust gases that are being used for process heating, and excess heat is also used to drive an absorption cooling system. In this paper, we will show a review on the studies of the trigeneration power plants in terms of components, modeling, optimization and decision-making techniques. For each section of the paper, a survey of previous studies with CHP/CCHP implementation is presented along with a survey of the methods used in their modeling, optimization, and decision-making. New topics are discussed concerning the cogeneration and tri-generation systems especially in the modeling, optimization and decision-making techniques. In almost all reviewed works, CCHP systems are found to have positive technical and performance impacts.

Key words: Cogeneration, CHP, trigeneration, CCHP, heat recovery, absorption chiller, decision-making, optimization.

INTRODUCTION

The electricity and energy sectors in the world are very important. In fact, the energy demand is increasing around the world each year, which lead to an increase in fuel consumption. This increase has led to a significant progressive growth in the energy shortage gap in many countries. Thus, energy usage must be optimized, the efficiency of the applied energy must be enhanced, and renewable energy sources must be used.

For building sectors, the energy consumption represents 32% of final total energy consumption and 40% of primary energy consumption in most IEA countries (International energy Agency). This energy consumption is mainly divided into electricity appliances consumption, space cooling, and space and water heating provided by the main electricity grid. For the space and water heating, it may be provided by separated fuel or gas boilers installed inside the buildings.

The production of heat and electricity separately is non-efficient. In fact, for the electricity production, the efficiency of an internal combustion engine and steam or gas turbines is about 40% (Martínez-Lera and Ballester, 2010; Al-Sulaiman et al., 2010). For the heat production, the efficiency of the boiler installed in the buildings sector is about 70% (Parliamentary Office of Science and Technology, 2005). Furthermore, the use of fuel in the conventional power generation systems result in an increase of the greenhouse gases emissions. To solve

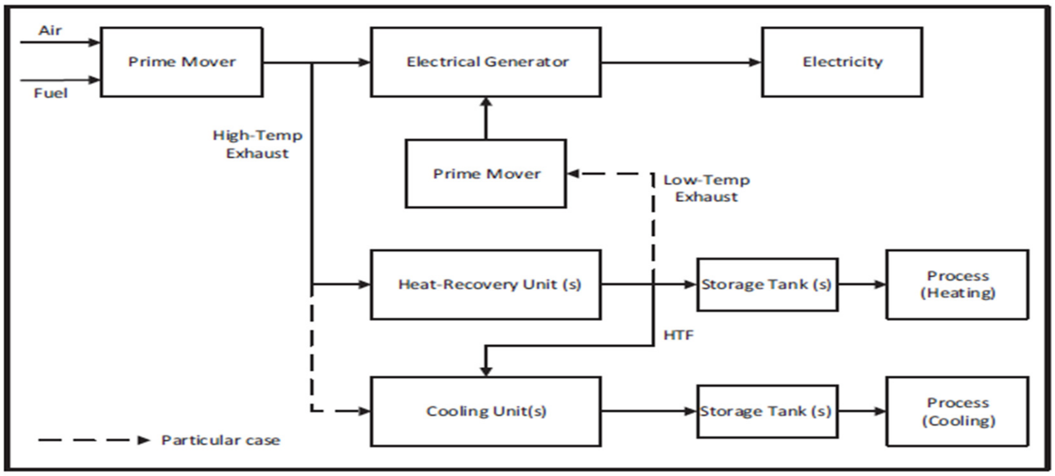

Figure 1. CCHP concept.

this energetic and environmental problem, it is recommended to install a cogeneration or a trigeneration system which will provide high efficiency with lower greenhouse gases emission (Mago and Chamra, 2009) and will be cost-effective (Ghaebi et al., 2012).

The objective of this paper is to provide a review about the technology, optimization and decision-making techniques of Combined Heating and Power generation (CHP) and Combined Cooling, Heating and Power generation (CCHP) systems. For this purpose, this paper is divided into five sections. After the first section, which is an introduction, in the second section the components of a trigeneration system are well defined and explained. In the third section, a review on the modeling and optimization techniques of a trigeneration system is introduced. In the fourth section, a summary of the decision-making technique is represented. Main conclusions are provided in the last section.

DEFINITION OF THE DIFFERENT COMPONENTS OF A TRI-GENERATION SYSTEM

A trigeneration system or CCHP is a system that generates power and thermal (heating and cooling) energy simultaneously from one source of fuel. The trigeneration plant is composed from the prime mover, a heat recovery unit, and an absorption or adsorption chiller. These components will be defined in details below.

Prime mover

The prime mover of a CCHP plant provides the mechanical motive power (Figure 1). Many types of prime movers are distinguished as follows:

(a) Steam turbines
(b) Gas turbines
(c) Combined cycle gas turbines
(d) Reciprocating internal combustion engines
(e) Microturbines
(f) Organic Rankine cycle
(g) Stirling engines
(h) Fuel cells

Steam turbines

Steam turbines are considered to be one of the most multipurpose and oldest prime mover technologies being used since about 100 years ago, when they replaced alternative steam engines, because of their high efficiency and low cost. The capacity of steam turbines can range from 50 kW to several hundreds of MWs for large power plants, which made these turbines widely used for CCHP applications. Their thermodynamic cycle is the Rankine cycle (Figure 2).

The cycle is the basis of conventional power plants and consists of a heat source (boiler) that converts water into high pressure steam. In the steam cycle, water is first pumped into the medium at high pressure. It is then heated to the boiling temperature corresponding to the pressure, boiled (heated liquid to steam), and often overheated (heated to a temperature above that of boiling). A multicellular turbine develops pressurized steam to lower the pressure. The water vapor is then escaped either to a condenser under vacuum conditions, or to a steam distribution system intermediate temperature whose role is to deliver steam to industrial or commercial application. Condensates from the condenser or steam system return to the water circulation pump for cycle continuation.

The two types of steam turbines often used are

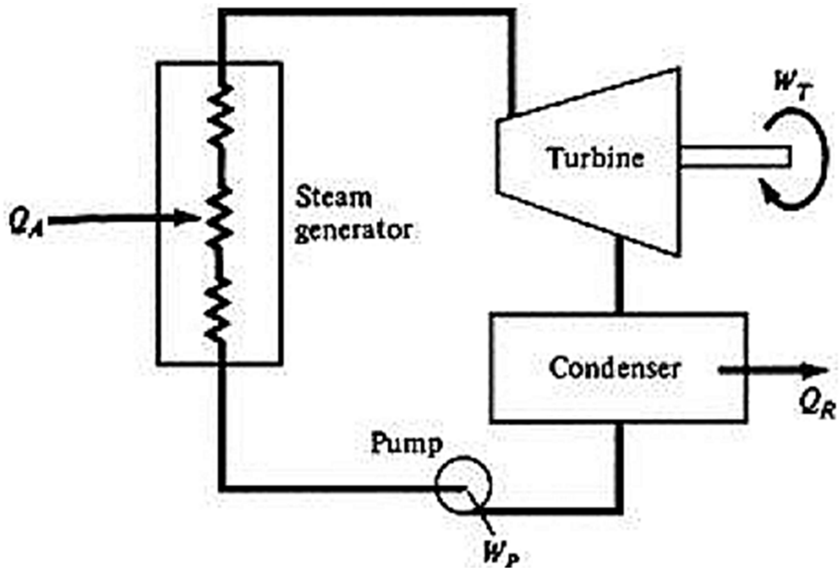

Figure 2. Steam turbine cycle.

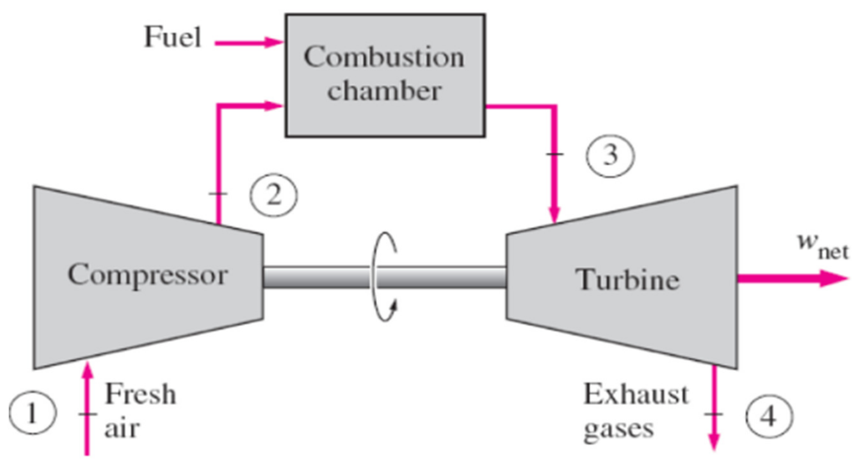

Figure 3. Gas turbine cycle.

backpressure and extraction condensation. The choice between the back-pressure turbine and the extraction condensing turbine depends mainly on the amount of electricity and heat, the quality of the heat, and the economic factors.

Gas turbines

Gas turbine systems operate on the thermodynamic cycle known as the Brayton cycle (Figure 3). In a Brayton cycle, atmospheric air is sucked into the compressor, where the temperature and pressure are raised. The high-pressure air passes into the combustion chamber, where the fuel is burned at constant pressure. Then the resulting high temperature gases enter the turbine, where they extend to atmospheric pressure through a row of vane blades (Sawyer, 1972). This expansion causes the turbine to rotate, which in turn rotates the inner shaft of a magnetic coil. When the shaft is rotating inside the magnetic coil, an electric current is produced (Lane, 2007). Two types of these turbines are available, the open-cycle gas turbines and the closed-cycle types (Petchers, 2003).

Gas turbine of a trigeneration system can produce all or part of the energy demanded from the site. The energy released at high temperature in the exhaust pipe can be recovered for various applications such as heating or cooling. Knowing that natural gas is the most commonly used, you can also use other fuels such as fuel oil or diesel. The typical range of gas turbines varies from a fraction of MW to about 100 MW.

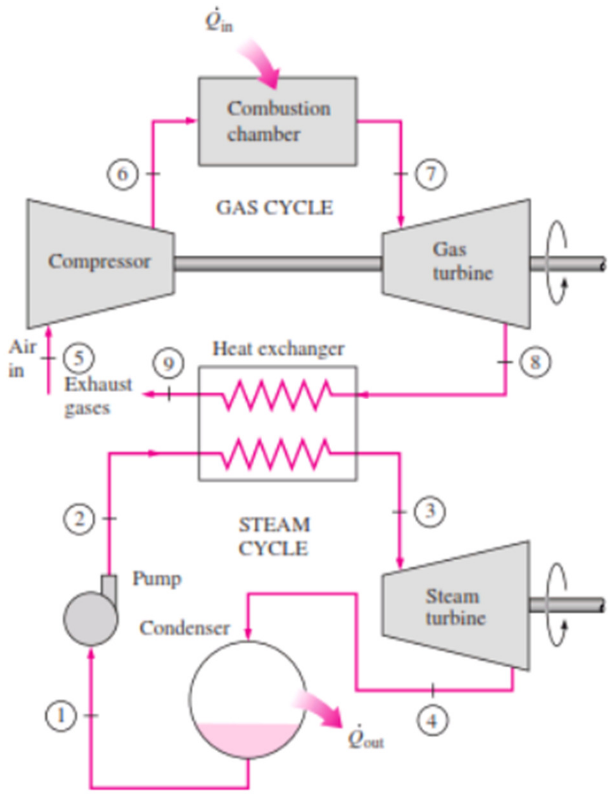

Figure 4. Combined turbine cycle.

Gas turbine has probably been the fastest growing in recent years due to the increased availability of natural gas, rapid technological advances, and significant reduction in installation costs and in environmental performance. In addition, the gestation period of the development of a project is shorter. Gas turbines have a short start-up time and provide intermittent operation flexibility. Although they have a low heat-to-power conversion efficiency (heat-force), more heat can be recovered at higher temperatures. If the heat output is lower than that required by the user, it is possible to have burned additional natural gas by mixing additive fuel with the oxygen-rich exhaust gas in order to stimulate thermal production in a more effective way.

Combined cycle gas turbines

Thermodynamics consists of two thermodynamic cycles, connected with a working fluid, and operating at different temperature levels. In the combined or closed system, the active fluid usually helium or air circulates in a closed circuit. It is heated in a heat exchanger before reaching the turbine, and is cooled after exiting the turbine, generating useful heat. Thus, the active fluid remains clean and does not cause corrosion or erosion (Figure 4).

The combustion of any external fuel can be considered a source of heat. In addition, nuclear or solar energies can be used. The efficiency range of a combined cycle CCHP systems is between 70 and 90%, and a power to heat ratio range from 0.6 to 2 (MITCO2, 2006).

Reciprocating internal combustion engines

Reciprocating combustion engines are widely used in traction and stationary applications for the drive of machines or alternators. They are composed from several cylinders in which the ignition of an air-fuel mixture generates a hot gas which pushes a piston. A crank-rod system transforms the translating motion of the piston into rotary motion and transmits energy to a shaft that drives the alternator (Lévy, 1996).

It can be either a spark ignition engine, mainly operating with natural gas and gasoline, or a compression ignition engine fueled by petroleum products like diesel.

There are four sources of waste heat that can be used from an alternating engine: exhaust gas, engine block cooling water, lubricating oil cooling water and turbocharger cooling (EA ICF Company, 2008). The recovered heat is generally in the form of hot water or low-pressure steam (<30 psig). Exhaust gases at high temperature can generate steam at medium pressure (up to about 150 psig).

Some industrial cogeneration applications use the exhaust from the engine directly for drying. In general, hot water and low-pressure steam produced by reciprocating engines are suitable for the Low temperatures (heating of premises, heating of drinking water) or to operate the absorption chillers that will be defined in the absorption chiller section.

These systems are well suited to a variety of decentralized production applications. These applications can be industrial, commercial and institutional. Reciprocating engines have a quick start, adapt well to the load and generally have a high reliability. In several cases, some units of alternative engines can increase the capacity and availability of the overall production. Reciprocating engines have a higher electrical efficiency than gas turbines of the same capacity, and therefore a low operating cost linked to fuels. In addition, the costs of AC generators are generally lower than those for gas turbine generators with a capacity of less than 5 MW (UNEP, 2006). The maintenance cost of AC motors is generally higher than that of gas turbines of the same capacity, but maintenance can often be handled by internal staff or by a local service company.

The decentralized potential production applications for reciprocating engines include monitoring, clipping, network support and cogeneration applications such as heating or cooling. Reciprocating engines are also widely used as direct mechanical pulsators for applications such as pumping water, compressing air and gas and cooling.

The economy of natural gas engines in on-site production applications is enhanced by the efficient use of heat energy in exhaust and cooling, which typically represents 60 to 70% of the energy of the input fuel (UNEP, 2006).

Wang et al. (2011) examined the performance and emission characteristics of a household sized trigeneration based on diesel engine generator using the ECLIPSE simulation software. Huang et al. (2011) used the same software to model and simulate a similar bio-fueled ICE trigeneration system in a commercial building. Khatri et al. (2010) have done a comparison of performance and emissions between a tri-generation system and a single generation one. Angrisani et al. (2012) investigated the on-site performances under real operating conditions of a micro-trigeneration plant. Rosato et al. (2013) conducted a dynamic performance simulation and assessment of micro-CHP systems for residential applications. Annual analysis of another engine trigeneration system was developed through computational simulation program by Santo (2014). Pagharini et al. (2012) used TRNSYS software tool to simulate an ICE trigeneration plant serving a hospital in Italy and checked its economic feasibility. Other studies in literature are as experimental such as those conducted by Angrisani et al. (2010), Easow and Muley (2010), Lee et al. (2013), and Rocha et al. (2012), or as models and simulations like those presented by Kavvadias et al. (2010), Rodriguez-Aumente et al. (2013), Angrisani et al. (2014), Espirito Santo (2012), Borg and Kelly (2013), Marimón et al. (2011), Puig-Arnavat et al. (2014), Wu et al. (2012), Balli et al. (2010), Jannelli et al. (2014), and Wang et al. (2010). In addition, Wang et al. (2014) showed in their work that the combined cooling and heating mode of a trigeneration system is far better than an independent HVAC system, through an energetic, economic, and environmental performance assessment.

Microturbines

The thermodynamic process of a micro-turbine is based on pressurizing the incoming air through the compressor. The compressed air and the appropriate fuel are mixed and burned in the combustion chamber. The hot gas resulting from combustion rotates the turbine by expanding. This actuates the compressor and supplies energy that rotates the turbine shaft of the compressor. With the aid of the recuperator, the hot exhaust gas makes it possible to preheating the air, which passes through the compressor to the combustion chamber (Onovwiona and Ugursal, 2010). The main components of the micro-turbine systems are the compressor, the turbine generator and the recuperator. Micro-turbine systems are reduced versions of combustion turbines that provide a reasonable electrical efficiency of about 30%, multi-capacity fuel, low emissions and heat recovery potential, and minimal maintenance requirements (Corp, 2000). For cogeneration applications, an overall efficiency of more than 80% can be achieved. The capacity of existing micro-turbine CSs varies from 25 to 80 kW. This range is appropriate to meet the thermal and electrical demands of residential, commercial or institutional buildings. In addition, research is continuing for systems with capacities less than 25 kW, for example, 1 and 10 kW (Pilavachi, 2002). This will be suitable for separate apartments. Micro-turbines offer a number of advantages over other CSs. These include compact size, low weight, low number of moving parts and reduced noise. In addition, micro-turbine CSs have a good quality of open heat, a low maintenance requirement (but skilled personnel), low vibration and a short delivery time. Yet, for lower powers other alternatives have better performance. Other fuels such as diesel, landfill gas, ethanol, industrial gases and other biological gases and liquids may be used other than natural gas (Pilavachi, 2002).

Organic Rankine cycle

An organic Rankine cycle (ORC) is based on the same principle of steam turbines but uses an organic working fluid (not water), having either a lower or higher boiling point than water.

Many studies are held concerning ORC. Maraver et al. (2014) executed a thermodynamic optimization of ORC for CCHP generation from biomass combustion; Cioccolanti et al. (2017) investigated the performance assessment of the small-scale integrated system in order to evaluate the potential feasibility of such a system for residential applications. Al Sulaiman et al. (2010) conducted an Energy analysis of a trigeneration plant based on solid oxide fuel cell and organic Rankine cycle. A modelling, simulation and a techno-economic assessment of biomass fuelled trigeneration system integrated with organic Rankine cycle was done by Huang et al. (2013). An exergy modeling is used to assess the exergetic performance of a novel trigeneration system using parabolic trough solar collectors (PTSC) and an organic Rankine cycle (ORC) (Sulaiman et al., 2011).

Stirling engines

Currently under development, a Stirling engine (SE) is an external combustion heat engine operating on Carnot cycle that encloses a fixed quantity of permanently gaseous working fluid like air or helium (Group, 2010). In typical SEs, about 30% of the heat input is converted to electric power and the rest is rejected to the cooling system and exhaust gases. With suitable thermal host, they can achieve CCHP thermal efficiencies approaching 80% (MITCO2, 2006; U.E.P.A. and EPA, 2007).

Fuel cells

Fuel cells (FCs) represent an entirely different approach of electricity production compared to traditional prime mover technologies. They are similar to batteries in producing a DC through an electrochemical process without direct combustion of fuel, but can operate indefinitely, provided a continuous fuel source is available and are more expensive than SEs, but generally show high electrical efficiencies under varying load. A FC operates when hydrogen and oxygen react in the presence of an electrolyte to produce water, which generates an electrochemical potential driving an electric current through an external circuit. Three basic components govern the operation of a FC: the reformer that extracts hydrogen from a gaseous fuel, the FC stack which is an electrolyte material placed between opposite charged electrodes, and the inverter where conversion of DC to AC power takes place (DOE, 2000).

In fuel cell CSs, the reaction of hydrogen with oxygen in the presence of an electrolyte takes place. This reaction has the role of producing electricity without combustion and without mechanical work. Water and heat are produced as by-products. The reaction is carried out by the electrochemical oxidation of a fuel (hydrogen) and the electrochemical reduction of oxygen. The following equations illustrate the electrochemical reactions:

At the anode: $H_2 \rightarrow 2H^+ + 2e^-$

At the cathode: $2H^+ + \frac{1}{2}O_2 + 2e^- \rightarrow H_2O$

The total reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

The total reaction is exothermic and, therefore, the heat released can be exploited to heat the premises and domestic hot water for residential, commercial or institutional applications. Hydrogen used as fuel can be produced from different sources such as natural gas, propane, coal, or by the electrolysis of water.

A fuel cell system consists of several subsystems, which include the core of the fuel cell and the auxiliary systems necessary for proper operation. The process of producing hydrogen from a fuel source such as natural gas is called reforming. The latter can be internal or external, depending on the type of fuel cell (Onovwiona and Ugursal, 2006).

There are several types of fuel cells at different stages of development. These types are: Alkaline Fuel Cell (AFC), Electrolytic Polymer Membranes (PEMFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), Oxide Fuel Cell solid (SOFC) and direct methanol fuel cell (DMFC).

Fuel cell technology is an important technology for power generation and cogeneration applications with performance and environmental benefits. The benefits of fuel cell CSs include low noise, low maintenance requirements, excellent load management, low emissions and potential for overall 85-90% efficiency, even with small units (Onovwiona and Ugursal, 2006). In the stationary power fuel cell, the natural gas is normally burned. This system releases less harmful emissions to the environment than a combustion cogeneration plant. With a fuel cell, emissions can be reduced by 49% for carbon dioxide, 91% for nitrogen oxide (NOx), 68% for carbon monoxide and 93% for organic compounds volatile (Scott, 1993).

Low emissions and noise levels make fuel cells well suited for residential, commercial and institutional applications. However, the main disadvantage of these batteries is their high cost and short life.

Malico et al. (2009) designed a trigeneration system using a high-temperature fuel cell (solid oxide fuel cells, SOFC) and an absorption chiller in order to meet the energetic demands of a hospital for electricity, cooling, heating and hot water. Chung Tse et al. (2011) investigated the feasibility of combining a SOFC-GT system and an absorption heat pump (AHP) in a trigeneration system to drive the heating ventilation and air conditioning (HVAC) and electrical base-load systems. They studied the thermodynamic model of various configurations and found an optimal configuration for this system. Elmer et al. (2016) provided an energetic, economic and environmental performance analysis assessment of a novel solid oxide fuel cell (SOFC) liquid desiccant tri-generation system for building applications. High efficiencies of trigeneration system are attainable at 68 to 71%. The inclusion of liquid desiccant increases the efficiency from 9 to 15% compared to SOFC electrical operation only. Meng et al. (2014) investigated an economic analysis of a solid oxide fuel cell in trigeneration systems for hotels in Hong Kong. They highlighted the suitability and the environmental impact of the SOFC-based multi-generation for building application in these buildings.

Heat recovery unit

Heat-recovery equipment is used in CCHP systems to capture thermal energy rejected from exhaust gas streams, liquid coolant circuits, or other sources and put it in a useful energy process. They thereby reduce fuel consumption and increase overall energy efficiency.

They are mainly composed of heat exchangers that differ in type according to the required application. Simple heat-recovery units function as heat exchangers by transferring thermal energy from one system to another.

These units are characterized as unfired heat-recovery units because they receive thermal energy from an independent heating source and have no ability to generate additional heat. More complex units are characterized as supplementary fired heat-recovery units because they include both heat transfer surfaces and fuel-firing equipment. These units are designed to supplement the heat provided by the primary heating source with thermal energy generated by combustion of additional fuel. Depending on the design of the installation and the process heating and power requirements, it may be necessary to use both fired and unfired heat-recovery units in the same CHP system (Oland, 2004).

Unfired heat recovery units

The unfired heat-recovery units are used in CCHP applications to extract heat rejected from prime mover. These units are not considered as sources of air pollution because they don't need to burn fuel in order to produce heat (ASHRAE, 2004). These units can be one of the following: heat exchangers, unfired heat-recovery steam generators (HRSG), mufflers, regenerators, and recuperators.

(a) Unfired HRSG: Unfired HRSGs function as heat exchangers by using the thermal energy in hot exhaust gases to produce steam and hot water. They are also called waste heat-recovery boilers (WHRBs) since they are fueled by the exhaust gases, and mainly applicable in gas turbines based CCHP systems (Kitto, 2004). Water-tube HRSG and fire-tube HRSG are two available configurations.

(b) Heat-recovery muffler: Heat-recovery mufflers are exhaust gas heat exchangers used to recover heat from reciprocating engine exhaust. Like HRSGs, they can generate hot water or low or high pressurized steam from the hot exhaust gases ranging from about 370 to 540°C, but with reduced noises (Orlando, 1996). However, exhaust gases temperature and composition vary from one engine to another; therefore, the amount of recoverable heat is influenced by the minimum stack exit temperature, which may be about 150°C or more (Oland, 2004). During operation, the excessive back-pressure must be taken into consideration that can be created on the engine, which reduces its capacity. Regular maintenance and cleaning are also needed (Orlando, 1996).

(c) Recuperator: Usually described as an air heater, a recuperator is a gas-to-gas heat exchanger that relies on tubes or plates to transfer heat from the hot exhaust gas stream to the cold incoming combustion air. Its components are arranged to prevent the two gas streams mixing. It is used in gas turbine and most microturbine CCHP systems, reducing the amount of fuel needed to heat the compressed air at the inlet of the turbines inlet, which lead to an increase in their energy efficiency. The problems that lead to a decrease in the effectiveness and the life cycle of the recuperator are corrosion, erosion, cost, high-temperature exposure, thermal stresses, and fatigue. These should be avoided by proper selection of materials during recuperators fabrication (Oland, 2004; Behbahani-nia et al., 2010).

(d) Regenerator: A regenerator is a gas-to-gas heat exchanger in which heat is transferred indirectly as a heat storage medium and is alternately exposed to hot and cold flow streams using rotary or valve switching device. During operation, a small but significant amount of air leakage occurs from one gas stream to the other. In principle, combustion air supplied to a gas turbine can be preheated in a regenerator using heat recovered from the hot exhaust gases, but significant technical and economic issues are associated with this application. Design challenges, economic issues, and high-temperature environment are major issues that severely restrict widespread use of regenerators in gas turbine CCHP applications (Oland, 2004).

(e) Heat exchangers: Beside the previous equipment, many other heat exchanger types can be used in the heat recovery process. Those can be shell and tube, plate, fins, or even micro-channeled heat exchangers.

Fired heat recovery units

Fired heat-recovery equipment serves two vital roles in

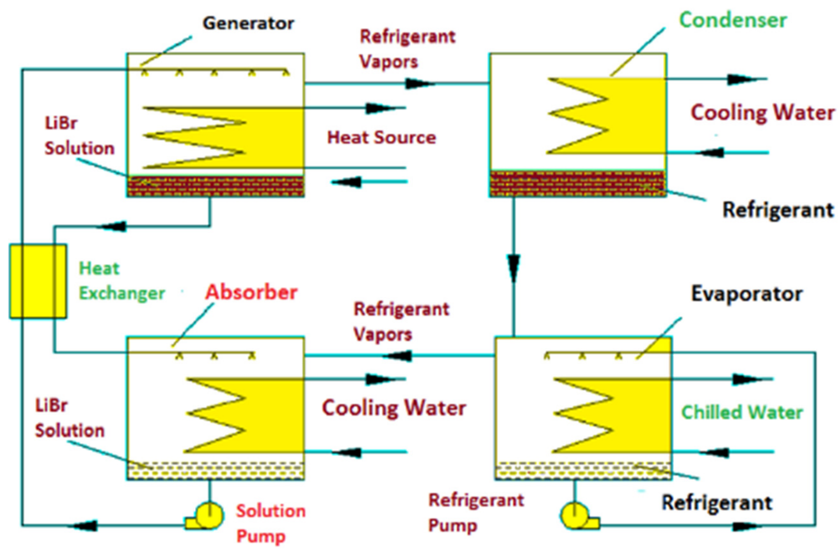

Figure 5. Single stage absorption chiller cycle.

CHP applications. As heat exchangers, the equipment extracts thermal energy exhausted from a heating source, and as combustion systems, the equipment uses chemical energy in fuel to produce additional thermal energy for the process. Two types of fired heat-recovery units are commonly used in industrial CHP applications. These units are known as supplementary fired HRSGs and ICI boilers. These units can be sources of air pollution when they combust fuel for complementary thermal energy required (Oland, 2004).

(a) Fired HRSG: It is usually used in gas turbines CCHP systems due to their high-temperature exhaust that contain sensible heat and rich-oxygen content (>15%), which can be used as combustion air to burn fuel for supplementary firing. Reciprocating engines do not operate with large quantities of excess air, so the oxygen content of the exhaust gases generally does not exceed 8%. With oxygen content, this low; recovering heat from reciprocating engine exhaust gases in a supplementary fired HRSG is generally not possible because the exhaust gases are incapable of supporting additional combustion. The HRSG is connected to the turbine by a ductwork containing the burner, which is designed to raise exhaust temperatures from less than 540°C to as high as 980°C. The design also provides flexibility with respect to the amount of steam produced, and should preferably have low NO_X emission levels (Orlando, 1996; Oland, 2002).

(b) Boilers: The general idea of integrating boilers in a CCHP application as heat recovery units is by using the heat rejected by the prime mover to produce more steam with less fuel. When used in this capacity, ICI boilers are often characterized as waste heat-recovery boilers WHRBs. They can be also classified either as water-tube or fire-tube boilers, with wide variety of designs and configurations depending on fuel type, emission control method, and other economic aspects (Oland, 2004).

Chiller

Thermal energy generated by prime movers can be used by chillers and dehumidifiers to produce a cooling rather than a heating effect, or to produce both. The wasted energy can be in the form of steam, hot water, or exhaust gas, and can fall into different temperature ranges. Therefore, the real success of a CCHP system requires that thermally driven cooling technologies be a good match for the prime movers (Deng et al., 2011; Wu and Wang, 2006) since each system has its own suitable working temperature.

Absorption chiller

An absorption chiller is a cooling machine that uses heat as the primary energy source (Figure 5). It is classified as indirect-fired, heat recovery or direct-fired units. The indirect-fired absorption chiller uses steam or hot water to produce a cooling effect. The heat recovery type uses gases rather than steam and hot water as a heat source and can be considered another type of indirect-fired absorption chiller. Direct-fired absorption chiller combusts fuel in burners to generate the required heat. It uses this heat in the heat exchanger of the absorber-generator part. The absorber-generator part of the chiller represents the thermal compressor instead of the electrical compressor in the electrical chiller. Indirect-fired chillers are well suited for CCHP applications being available in capacities ranging from 100 to 1500 tons (Oland, 2004). Single-stage absorption chillers can operate on low temperature hot water or low-pressure steam (0.8–1 bar). They typically use LiBr– water pair in applications that do not require operation below 0°C since the water would freeze. Otherwise, water–ammonia mixture would be used. Yet, more efficient double and triple-stage absorption chillers require higher temperature and pressure levels (Orlando, 1996; Petchers, 2003).

Adsorption chiller

Adsorption chiller is an environment-friendly and effective novel technology in the use of low grade heat sources. As in absorption, an adsorbent and refrigerant form a working pair. Their selection depends mainly on their thermodynamic, chemical, and physical properties, in addition to cost and availability measures (Askalany et al., 2013; Alghoul et al., 2007; Wang et al., 2010; Christoph, 1996; Wang and Oliveira, 2006). The operating procedure of such working pairs can be physical or chemical and the adsorbents can be pure, composites, or compounds with various characteristics. For example, adsorption chillers using silica gel–water working pairs have been well accepted and thus commercialized since they can be powered with 60–90°C hot water directly (Deng et al., 2011; Wang and Oliveira, 2006).

Desiccant dehumidifiers

Solids and liquids that are capable of attracting and holding moisture are known as desiccants. Some common desiccants include silica gel, activated alumina, alumina oxide, and deliquescent absorbents such as lithium chloride (LiCl) and calcium chloride ($CaCl_2$). Although removing moisture from air using a desiccant slightly increases the air temperature, less energy is required by a chiller to cool the dehumidified air. Humidity control is another important aspect of space conditioning for comfort cooling. Maintaining the humidity of a conditioned space below 60% relative humidity minimizes the growth of mold, bacteria, and other harmful microorganisms. Desiccant dehumidifiers use heat to achieve a cooling effect by removing water vapor from an air stream and thereby decrease the latent cooling load. When desiccants become saturated, they lose their ability to remove moisture and must be either replaced or recharged. Recharging a desiccant involves increasing its temperature to expel the captured moisture. The recharged desiccant is then capable of attracting and holding additional moisture. Heat recovered from CCHP systems is suitable for recharging most desiccants.

There are five basic types of desiccant dehumidification: the liquid spray towers, solid towers, rotary dehumidifiers, multiple vertical bed system and desiccant wheels.

In practice, desiccant dehumidifiers are designed to operate either independently of the chiller or in series with the chiller (Oland, 2004).

MODELING AND OPTIMIZATION

Several studies have been done regarding these systems. The most interesting study is the integration of such systems in an electrical network. The problem of the integration of CHP or CCHP systems is, according to all the publications, based on two subjects: economy and pollution. Several mathematical functions concerning the integration of cogeneration systems have been discussed previously. These functions consider only the economic aspects and the data concerning their degree of pollution. At the economic level, there are three themes to which the mathematical functions correspond. These three themes are: the total investment cost, the cost of production and exploitation as well as the profit.

The total cost of investing in CCHP is highlighted in (Satoshi et al., 2002; Carpaneto et al., 2011a, b; (Pires et al., 2013; Hong and Chih-Yuan, 2002).

The problem addressed in the total investment cost studies is to establish a general objective function for optimization and scheduling, which sums up the costs of installation, investment and operation of cogeneration systems.

Satoshi et al. (2002) introduced an objective function that represents the minimization of the estimated annual value of the total cost using the hierarchical optimization algorithm with a sensitivity analysis.

Carpento et al. (2011a, b) introduced an objective function that calculates the annual cost of integrating cogeneration systems using Monte Carlo simulations to determine the occurrences of energy cost in multiple time intervals.

Pires et al. (2013) introduced an objective function that represents a minimization of the sum of the specific costs using differential evolution (DE), particle swarm (PSW), simulated annealing (SA), genetic algorithm (GA) and pattern search (PSE). The response surface method is used to reduce the number of evaluations of the "objective" function using all the algorithms, in order to obtain the optimal result.

For Hong and Chih-Yuan (2002), the problem is the minimization of the total cost. The latter depends on the price of fuel and its enthalpy, the cost of transmission and total production. The mathematical method used to solve the problem is the Genetic Algorithm (GA).

The cost of producing and operating a CCHP system is presented in (Tsay et al., 2001, 2000; Tsay, 2003; Guo et al., 1996; Brannlund et al., 2012; Ashok and Banerjee, 2003; Sandou et al., 2005; Kong et al., 2005;

Frangopoulos and Dimopoulos, 2004; Azit and Nor, 2009; Divényi and Dán, 2011).

The production cost problem considers the operation costs of the integrated cogeneration system. This problem requires a realistic study of the system in order to find the appropriate operational strategies. This cost is particularly influenced by the mode of use of fuels and their relative electric and heat efficiencies in the system.

Tsay et al. (2001) used an objective function that corresponds to the minimization of the cost of the cogeneration system in the industrial sector. In fact, the calculated cost is dependent on the price of the fuel mixture, the enthalpy of the boilers and the cost of electrical exchange with the network, as a function of the time of use of the system (TOU).

To solve the problem, they used the evolutionary programming (EP) (Tsay et al., 2001, 2000; Tsay, 2003).

Guo et al. (1996) used an objective function whose purpose is to minimize the production cost of the system. This objective function is the sum of the costs of the electric power of the conventional generators, the thermal power of the boilers and the electrical and thermal power of the cogeneration system. The method used to solve the problem is an algorithm proposed by the authors that has 7 iterations.

The purpose of the "objective" function used by Brannlund et al. (2012) is the minimization of the economic dispatching. The latter is equivalent to the production cost distributed on all generators. It is calculated based on the operating costs of gas turbine generators, steam turbine generators, diesel generators and boilers. These costs are represented according to the electrical and thermal powers. The problem is solved using the MINOS software. The latter is used to solve nonlinear "objective" functions.

The objective function used by Ashok and Banerjee (2003) minimizes the total monthly cost of the operation. It is represented in terms of operating costs (including maintenance costs) of gas turbines, steam turbines, boilers, heat recovery boilers, the cost of importing and exporting energy and demand. The resolution method used is the Quasi-Newton method.

The "objective" function used by Sandou et al. (2005) represents a minimization of production costs. It is based on the costs of thermal production, starting and stopping boilers, and the costs of electricity production, starting and stopping turbo-generators and the electrical power produced by them. The mathematical method used to solve the problem is Branch and Bound.

The "objective" function used by Kong et al. (2005) represents a minimization of the energy cost. It is calculated from the cost of natural gas purchased and used in gas turbines, absorption chillers and heat recovery boilers and the cost of purchased electrical energy. The mathematical method used to solve the problem is Linear Programming.

The "objective" function used by Frangopoulos and Dimopoulos (2004) is the minimization of the operating cost of the cogeneration system. It is based on operating cost rates to cover energy demand and penalty if energy is not covered, considering taxes, depreciation rate of system capital and profit from the sale of electricity.

The method used to solve the problem is the Genetic Algorithm for calculating the optimal values of the integer variables, and the approximation of the optimal values of the real variables. Then, the second method used is the Deterministic Algorithm to find the optimal value of the real variables. In addition, a sensitivity analysis using the State-Space Method (SSM) is performed to apply the Intelligent Functional Approach (IFA) to obtain the third set of optimal solutions for partial failure operation (Frangopoulos and Dimopoulos, 2004).

The "objective" function of Azit and Nor (2009) represents the total weekly cost. It is based on fuel costs, peak and off-peak energy, water used, demand charges at peak and off-peak hours, and electrical energy exported to the grid. The problem is solved using the Integer Programming technique. After introducing the binary digits obtained, the total problem is solved using Bellman's principle of optimality (Dynamic Programming).

The model studied for the cost of production by Divényi and Dán (2011) is the value cost of the units of the distributive production (DG). It is a function of the electrical power, the reserve energy and the reserve price of each unit. The resolution method used is an algorithm proposed by the authors. The latter consists of three stages: filtration, qualification and optimization.

The problem concerning the profit is to calculate the added value of the cogeneration system integration. He has as goal in the calculation of the economic benefit in order to show the importance of this integration.

In Carpaneto et al. (2011b), the Discounted Payback Period (DPP) is defined as the difference between the total cost of the system when integrating the cogeneration system and the total cost of the system without this integration. In (Frangopoulos and Dimopoulos, 2004), the Net Present Value (NPV) of the investment is calculated in function of the investment cost without subsidy, the annual profit of the operation year (including the taxes) and the present worth of the salvage value of the system at the end of the period studied. In (Azit and Nor, 2009), the second function presents the benefit of the system in function of the strategies of performance (control, change of number of operating units, efficiency, consumption of fuels, thermal service). In (Tsay and Lin, 2000), the function highlights the cost of fuels used in several types of boilers (high-pressure and medium-pressure), the cost of the electrical exchange with the network and the cost of the industrial water. In (Furusawa et al., 2006), two objective functions are presented. The first calculates the electricity cost at the utility level with regards to the DC optimal flow. It is calculated as a function of the fuel cost, the start-up cost and the subsidy provided to the customer. The second function calculates the electricity cost at the client level. It is calculated as a function of the demand charge, the energy cost (including the cost of electricity exchange), the cost of the energy equipment and the cost of the cogeneration system equipment (including the subsidy). The objective function in Schellong and Schmidla (2013) is calculated in function of the revenues (electrical and thermal), the maintenance cost, the fuel cost and the operating cost. It considers the unit's availability due to the maintenance and the errors that can occur. In (Reidhav and Werner, 2008), the Net Present Value (NPV) is calculated according to the revenue of each unit, to the heat supplied by each one, to the production cost of heat, to the thermal losses and to the service and maintenance cost. In (Rezvan et al., 2012), the objective function is calculated in function of the variable cost, the cost of the gas consumed by the system and the boilers, and the electricity cost.

In the preceding below, the models studied correspond to the economic functions. In this section, the models studied correspond to the pollution and emissions of the cogeneration system. The calculation of pollutant emissions is intended to highlight the degree of pollution to consider the mode of operation of cogeneration systems. In fact, the type of fuels and the power of the generators have a great effect on the pollution.

The model of Tsay et al. (2001, 2000) and Tsay (2003) used highlights the minimization of polluting emissions. It considers the NOx and SOx emissions calculated according to the enthalpy of the fuels. In addition, the model after Tsay (2003) highlights CO_2 emissions. The mathematical method used to solve the problem is evolutionary programming (EP - Evolutionary Programming). In (Furusawa et al., 2006), the "objective" function calculates the CO_2 emission according to the output power of the generators and the use of gas. The method used to solve the problem is General Algebraic Modeling System (GAMS).

As we can see, a number of researches have worked on the use of many modeling and optimization theories on the analysis of cogeneration and trigeneration systems. There are many factors that influence on the optimization of a cogeneration or a tri-generation system. Thus, the optimization could be difficult since many variables should be taken into consideration. Therefore, Multi-objective optimization concept was applied by many authors using the Pareto front figures to find the system characteristics and to find the best performance by considering two or more objective functions at the same time. Evolutionary algorithms were applied in other studies in the optimization of a trigeneration plant.

DECISION-MAKING STRATEGY

In previous work, Tsay et al. (2001) calculated the power that must be imported to obtain the minimum cost of production, and the power that must be imported to obtain the minimum emissions. In addition, they proposed a distribution strategy that might be appropriate for policymakers. In Tsay et al. (2000), they also considered environmental constraints in calculating the optimal cost in peak, half-peak and off-peak periods. And in Tsay (2003), they deduced that a minimum cost of production corresponds a maximum pollution and vice versa. Frangopoulos and Dimopoulos (2004) used the Genetic Algorithm (GA) with a sensitivity analysis to find the number of cogeneration systems to be installed for given capacities, regardless of environmental constraints. In fact, the capacities of the systems were specified, so they only had to choose the quantity of cogeneration systems to install. Furusawa et al. (2006) studied the cost of production under environmental constraints. They concluded that even if installed cogeneration systems have a large capacity, they are still effective in reducing primary energy consumption and polluting emissions (CO_2). Freschi et al. (2013) found compromise solutions by applying the weighted sum method for economic and environmental assessments. This method did not result in a single solution. Indeed, different solutions are found by modifying the weighting. This method cannot be considered clear and precise.

From the mentioned works, there is no strategy of choice which leads to selecting the best power of a cogeneration system to be installed with an economic-environmental compromise.

In addition, there are many decision-making techniques used with multi-objective optimization. Perera et al. (2013) used the Fuzzy TOPSIS technique (Behzadian et al., 2012) of multi-criteria decision making to design a hybrid energy system. They combined this technique with Pareto multi-objective optimization. In the mentioned technique, the solution is obtained by a weighted decision matrix. Therefore, TOPSIS Fuzzy is a weight-based estimation technique suggested by decision makers. Chaudhuri and Kalyanmoy (2010) used an interactive multi-criteria decision-making method. The method is based on: the weighted sum approach, the function-based approach of the distribution service, and the Chebycheff function approach. Thus, they used compromise information between goals. The result is obtained through the decision maker's opinion, which is based on estimates. Pedrycz and Song (2011) used the methods of Analytic Hierarchy Process (AHP) (Saaty and Ozdemir; 2003; Saaty, 1987a, b, 1983; Saaty and Hu, 1998) and granularity information. Decision makers must choose a reciprocal matrix and a level of granularity. Huang (1997) used fuzzy set theory and weights applied to each objective according to its importance. Niknam et al. (2012) used a fuzzy decision algorithm (Fuzzy) based on the weighting factors selected by the operator according to the importance of the objective function. Miettinen et al. (2014) used elements of the multi-objective optimization method NIMBUS (Miettinen, 1999; Miettinen and Mäkelä, 2000, 2006) of interactive classification. In this method, optimal solutions of Pareto have been obtained by solving a problem that includes preference information given by the decision maker in the form of classifications. And they used estimation-based constants to stagger objectives. Gunawan and Azarm (2005) tested the robustness of the design. As a result, the set of robust designs was considered as a set of optimal solutions, hence Pareto solution. Dowhan et al. (2009) used the AHP method with Pareto optimality. Yang and Lingfeng (2012) used the weighted aggregation approach method that converts a multi-objective problem into a single-objective problem by multiplying each goal with weights defined and estimated by the user and the decision maker. Dufo-Lopez et al. (2011) used many control strategies for energy production to find the best result of the "Pareto front". Al Asmar et al. (2017) introduced a new decision-making technique that is used to find a cogeneration power that respects the economy and the environment by multi-physical modeling of the integration of cogeneration systems in an electrical network, and a “multi-objective" optimization dealing with the economy and pollution factors. This power illustrates the best compromise between total cost and pollutant emissions (CO_2). Thus, they introduced subsidies from the distribution service in the form of a motivational factor and demonstrated their impact on decision-making. Al Asmar et al. (2016) introduced a novelty in selecting the best solution proposed by a heuristic multi-objective optimization method (Genetic Algorithm).

Conclusion

Trigeneration or Combined cooling heating and power (CCHP) system is an efficient energy production solution. In this paper we highlighted the different composant of this system. The prime mover of a CCHP system can be a steam turbine, gas turbines, microturbines, internal combustion engines, organic Rankine cycles, Stirling engines, and fuel cells. Two or more of these can be installed to form a combined cycle. Then heat recovery equipment are presented and divided into heating units, which include fired and unfired heat recovery steam generators, various heat exchangers, boilers, and cooling units like absorption or adsorption chillers and desiccant dehumidifiers. For each part, a comprehensive review of conducted studies is presented. Furthermore, an overview on the studies concerning the modeling and optimization methods of CCHP system is presented. Finally, a general selection approach must be adopted for a CCHP system. Moreover, a review on the decision-making techniques is resumed in this paper. Thus, to realize a CCHP project, a good selection and design of the components suitable together must be made, an economy and environmental modeling, optimization and a decision-making technique must be adopted for the best power to be implemented.

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