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Multi-objective optimization of CCHP system with hybrid chiller under new electric load following operation strategy

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Abstract

The performance of combined cooling, heating and power (CCHP) system is greatly affected by its operating strategy and design. In this paper, a new electric load following (NELF) strategy was developed. It is based on the alternation between absorption cooling and electric cooling according to the building energy requirements, for hybrid chiller based CCHP systems. A comparison of the new proposed strategy with the modified electric load following (MELF) and electric load following (ELF) strategies is performed. A multi-objective optimization approach based on genetic algorithm is carried out to predict the optimal capacity of CCHP systems. Performance criteria like primary energy consumption, annual total cost and carbon dioxide emission were considered as objective functions. The performances of these CCHP systems and operation strategies were examined and compared with the separated production (SP) system for a Mosque complex located in Algiers, Algeria. Results show that hybrid chiller CCHP based NELF strategy is the best choice, which can reduce the primary energy consumption by 34.45 GWh/year, annual total cost by 0.313 million €/year and CO₂ by 8.37 kton/year. Compared to the other configurations and strategies, the hybrid CCHP based NELF achieves better energetic, economic and environmental performance under the optimized conditions.

Keywords: Combined cooling, heating and power system; Electric load following strategy; Hybrid chiller; Multi-objective optimization.

Nomenclature

AC	absorption chiller	
ATC	annual total cost	(€)
$ATCSR$	annual total cost saving ratio	(%)
C	cost	(€)
$CCHP$	combined cooling, heating and power generation system	
CDE	carbon dioxide emissions	(kg)
$CDERR$	carbon dioxide emissions reduction ratio	(%)
COP	coefficient of performance	
E	building electric load	(kWh)
E_{Ec}	electric energy consumed by the electrical chiller	(kWh)
E_{Grid}	electric energy consumed from the grid	(kWh)
E_{PGU}	electric energy generated by the power generation unit	(kWh)
E_{PGU}^{MAX}	power generation unit capacity	(kW)
EC	electric chiller	
ELF	electric load following	
F_B	boiler fuel consumption	(kWh)
F_{Grid}	grid fuel consumption	(kWh)
F_{PGU}	power generation unit fuel consumption	(kWh)
$MELF$	modified electric load following	
$NELF$	new electric load following	
Q_B	heat generated by boiler	(kWh)
Q_c	cooling load	(kWh)
$Q_{c,Ac}$	cold generated by absorption chiller	(kWh)
$Q_{c,AC}^{MAX}$	absorption chiller capacity	(kW)
$Q_{c,Ec}$	cold generated by electrical chiller	(kWh)
$Q_{c,EC}^{MAX}$	electrical chiller capacity	(kW)
Q_h	heating load	(kWh)
Q_{Rc}	heat required for cooling	(kWh)
Q_{Rec}	recovered heat	(kWh)
PEC	primary energy consumption	(kWh)

$PESR$	primary energy saving ratio	(%)
η_B	boiler efficiency	(%)
η_e	power generation unit electrical efficiency	(%)
η_e^{SP}	grid power generation efficiency	(%)
η_{Grid}	grid distribution efficiency	(%)
η_{Rec}	heat recovery system efficiency	(%)

1. Introduction

During the past century, fossil fuels (natural gas, oil, and coal) were the major primary source of energy in the world, and provided 85–93% of all energy production from 1950 to 2005 [1]. According to [International Energy Agency \(IEA\)](#), the global energy demand will continue to rise by 30% from 2015 to 2040 [2]. If this growth is covered by conventional power plants, it may cause negative economic and environmental implications.

In conventional power plants, the electricity conversion efficiency ranges from 30 to 50% [3]. Conventional thermal power plants discharge large amounts of heat in the atmosphere. Recovering all or part of this heat can increase the overall energy efficiency of power plants. Additional energy losses also appear in the transmission and distribution of electric energy [4]. Distributed generation, described as power generation near to final consumer, can minimize the transmission losses [5]. Thus, the combined production of cold, heat and electricity (CCHP) from a primary source of energy, which is called too as trigeneration, is seen as a promising solution for satisfying and solving energy-related problems with high technical, economic and environmental benefits [6]. CCHP systems generated more than 11% of national electric power for the G8 countries in 2006 recovering exhaust heat for both heating and cooling of buildings and in industrial processes. This share is expected to reach 24% by 2030 [7].

The CCHP system concept is simple: electricity is produced via a power generation unit (PGU). The heat rejected by the PGU can be recovered by another integrated system to provide the primary energy for the cooling and heating load in buildings and in industrial processes. Generally, a simple CCHP system is composed of PGU, heat recovery system, absorption chiller units (AC) and a heat exchanger. The absorption chiller can be driven by the rejected heat of the PGU to meet cooling demand [8]; the heat recovery system is installed to recover the rejected heat to be able to satisfy the heating demand.

Compared to conventional separated energy production system (SP), in which the electricity demand is satisfied by the electricity purchased from the grid and/or the thermal demand is satisfied by burning a fuel in a boiler, the CCHP system benefits of higher energy efficiency and lower pollutant emissions [9]. Therefore, the objective of designing CCHP systems aims to minimize primary energy consumption, annual cost, and greenhouse gas emissions as

much as possible. To attain this, the following issues should be taken into consideration in the design of such system: the operating strategy of the system, the efficiency of each component and the requirements of building for electricity, heat and cold [10].

In general, there are two fundamental operation strategies for CCHP system: electric load following (ELF) and thermal load following (TLF). The evaluations and analyses of each of these two strategies are examined in [11–14], where the major previous studies found that ELF strategy can achieve better energetic and environmental performance compared to TLF strategy.

When the CCHP system operates under ELF strategy, the system delivers sufficient electricity for the building first and takes advantage of the by-product heat to meet all the thermal demand. If the by-product cannot satisfy the thermal needs, an auxiliary boiler should be implemented. When the CCHP system operates under TLF strategy, the system meets all the thermal demand of building first. If the electrical power generated by the PGU cannot meet all the electric demand, additional electric power should be imported from the national grid. However, if electrical power generated by the PGU exceeds the demand, excess electricity could be transferred to the electric grid.

In addition to the researches in operation strategies of CCHP systems, there are also some studies on the cooling methods. Typically, CCHP system uses absorption chiller to meet the cooling demand. Therefore, in such systems, owing to the relatively low coefficient of performance (COP) of the absorption chillers machine, the energy consumption of CCHP systems can be higher than conventional systems [15]. However, a hybrid system with absorption chiller and electric chiller (EC) can be an attractive method to satisfy the cooling demand, that may help matching the ratio of the power and heat provided by PGU with user loads considerably better [16]. Nevertheless, taking into account the high rates of the electricity, an operation strategy requires to be designed to identify the optimal electric/absorption cooling ratio. To increase the performance of this strategy, other researchers have suggested to use optimal electric/absorption cooling ratio that may improve energy, economic, and environmental performance of the hybrid chiller CCHP system. Wang et al. [17] applied the particle swarm optimization algorithm (PSOA) to the design and operation of the CCHP system by optimizing the capacity of the PGU, the storage

tank and, the rate of electric cooling to total cooling load in order to achieve the highest energy, economy and environment performances of the CCHP system. Hajabdollahi et al. [18] examined the variable electric/absorption cooling ratio strategy with the constant electric/absorption cooling ratio strategy for several climates, where they found that the variable electric/absorption cooling ratio strategy provided more benefit in the all studied climates. Li et al. [19] optimized the energetic, economic and environmental performance of CCHP system with hybrid chiller. The authors found that if the CCHP system couples with thermal storage and renewable energies systems, the performance of the CCHP system increases significantly. Li et al. [20] performed energetic and exergetic comparison between absorption chiller and electric chiller in CCHP system which functions with a combined cycle of gas turbine and steam turbine as prime mover. It has been shown that the choice between these two types of cooling is strongly dependent on the distance between the power plant and the cooling device, in a way that when the distance is less than 5 km, absorption cooling system is more effective. Hyeunguk et al. [21] proposed the modified electric load following strategy (MELF) for CCHP system which uses a hybrid chiller which combines electric chillers and absorption chillers based on two U.S. Department of Energy reference buildings located in two different climates. Their results showed that the hybrid chiller based CCHP systems with new MELF strategy achieves lower energy consumption and carbon dioxide emissions than the absorption chiller based CCHP systems.

The economic aspect is one of the main concerns in CCHP system design. Different techniques must be investigated and the one that satisfies utility demands with the lowest annual cost is usually adopted [22]. Ziher et al. [23] examined economic feasibility of CCHP implemented in one of the largest hospitals in Slovenia. The trigeneration system consisted of a natural gas turbine and steam absorption along with compression chillers with cold storage. The pay-back period of this system was 5.8 years. Pagliarini et al. [24] optimized and analyzed the feasibility of a CCHP system for a hospital in Parma, Italy, by minimizing the total operational and maintenance cost. The economic analysis showed that the suggested CCHP system can be paid back in a period of about 15 months. Gu et al. [25] studied the performance of CCHP systems for residential buildings in Shanghai, China, using several management options and designs. The most advantageous option was a CCHP system with gas engine under energy island mode. Moreover, the CCHP system has the ability to

decrease primary energy consumption and carbon dioxide emission by 17% and 40%, respectively. However, the net present value is -0.5 million USD. This shows that CCHP systems are not always suitable to be introduced in residential buildings in Shanghai. Chua et al. [26] evaluated several CCHP system configurations by combining various prime mover technologies. The systems had been designed for the tourist island of Pulau Ubin, Singapore. Amongst all combinations of the different primary mover technologies, the economically optimum combination can contribute to 20% renewable energy integration into the CCHP system with a gain of 0.15 million USD per year. Abbasi et al. [27] designed and analyzed a CCHP system with gas turbine (GT) and IC engine for a residential complex located in Shahrood, Iran. It was shown that the combination of diesel engine and gas engine under ELF strategy is the best option producing 87, 62.8 and 80% of energy efficiency, exergy efficiency and cost saving, respectively. Hyeunguk et al. [28] studied the economic performance of hybrid chiller CCHP systems, under MELF strategy, applied for a large office building in three different regions in the United States. The authors reported that CCHP systems can decrease the annual operation cost by up to 0.4 million USD per year (38%) compared to the conventional system in the best case. In any case, the economic feasibility of CCHP systems is considerably affected by the energy prices that vary from one region to another.

As described above, a good CCHP system should generate economic savings, energy savings as well as reductions in pollutant emissions. The performance of the CCHP system depends closely on its operation strategy and configuration. In order to maximize the benefit of the CCHP system, it is important to optimize the design parameters of the CCHP systems such as the capacity of the facilities. In the case of SP system, this capacity is easy to specify because the size depends directly on the energy load of the building [6]. On the other hand, as a result of the complexity of operation strategies, the capacity of facilities is hard to be determined in the CCHP systems [6]. Considering the prices of facilities, grid electricity cost and fuel rates, some multi-objective optimization approaches have been adopted to determine the optimal capacity of facilities in order to maximize the energetic, economic and environmental benefits of CCHP system [29].

Some researchers have adopted conventional multi-objective optimization methods such as weight method [30–32] and ϵ -constrain method [33–35]. The weight method is widely used due to its simple procedure. However, it is not easy to determine the weight of each

objective and an insufficient number of Pareto solutions would be generated with a weight method, which makes it difficult to exactly reach the Pareto front [29]. On the other hand, the ϵ -constraint method suffers from its computational complexity which is considerably higher than the weight method, and only a local optimum is obtained by using this method. This means that the global optimum relies on the initial guess [29].

In order to deal with the limitations of classical methods, evolution-based algorithms have been adopted for CCHP system optimization. The most common evolution-based algorithm used in CCHP system is the non-dominated sorting genetic algorithm-II (NSGA-II) [36–39], which has been proved to be one of the most effective multi-objective optimization algorithms capable of seeking a much better solution range and better convergence close the Pareto-optimal front relative to other multi-objective evolution-based algorithms [40]. Therefore, the NSGA-II is adopted in the present study to determine the optimal capacity of facilities.

In view of this, energetic, economic, and environmental optimization of a new proposed electric load-following strategy for CCHP systems equipped with hybrid chillers has been carried out in this study. The new strategy, proposed by the authors, was investigated and compared with the existing electric load following strategies for a Mosque complex located in the north of Algeria. The new strategy for CCHP systems with hybrid chillers was examined with consideration to the primary energy consumption, annual total cost and carbon dioxide emission. Multi-objective optimization method using NSGA-II algorithm was employed to obtain the Pareto front. The final optimal solutions among the possible solutions located on the Pareto fronts are chosen by using decision-making methods with the aim of choosing the best capacity of the power generation unit, absorption chiller, and electrical chiller to maximize the performance of each system and strategy. The primary energy saving, annual total cost saving and carbon dioxide emission reduction obtained with the new strategy, under the optimized parameters, are assessed and compared with those of the other electric load following strategies. Finally, the effect of the chiller type and the operation strategy, to support the building load, on the performance of the systems are discussed and compared based on the integrated analysis. The paper is structured in the following manner. First, the case study and its heating, cooling, and power requirements are described in Section 2. Section 3 presents the description of CCHP systems and the conventional SP system, where

the mathematical models of the strategies based on energy flow were established. Section 4 focuses on the suggested approach for solving the multi-objective optimization problem, where the NSGA-II algorithm and decision-making approaches are described. Section 5 discusses the optimization results and compares the performance of the new suggested strategy with the other strategies. Finally, the related conclusions are drawn in Section 6.

2. Case study

The Algerian state has launched the construction of a new national landmark "Great Mosque of Algeria", 500 meters away from Algiers Bay, in the Mohamadia province. The Mosque is the third-largest in the world (Fig. 1) with a floor area of about 400,000 m², and is expected to host more than 120,000 visitors daily. The minaret of the Mosque will be the world's tallest at a height of 265 meters (the highest building in Africa), and will include a museum, research facilities and a visitor's platform (Fig. 2). The Mosque complex will also include a convention center, a library and a university. A passage will ensure the transport connection between the underground car park in the basement of the Mosque, which is designed to accommodate more than 4,000 parking spaces, and the city highway, from which two passages provide an urban connection to the Mediterranean coast.

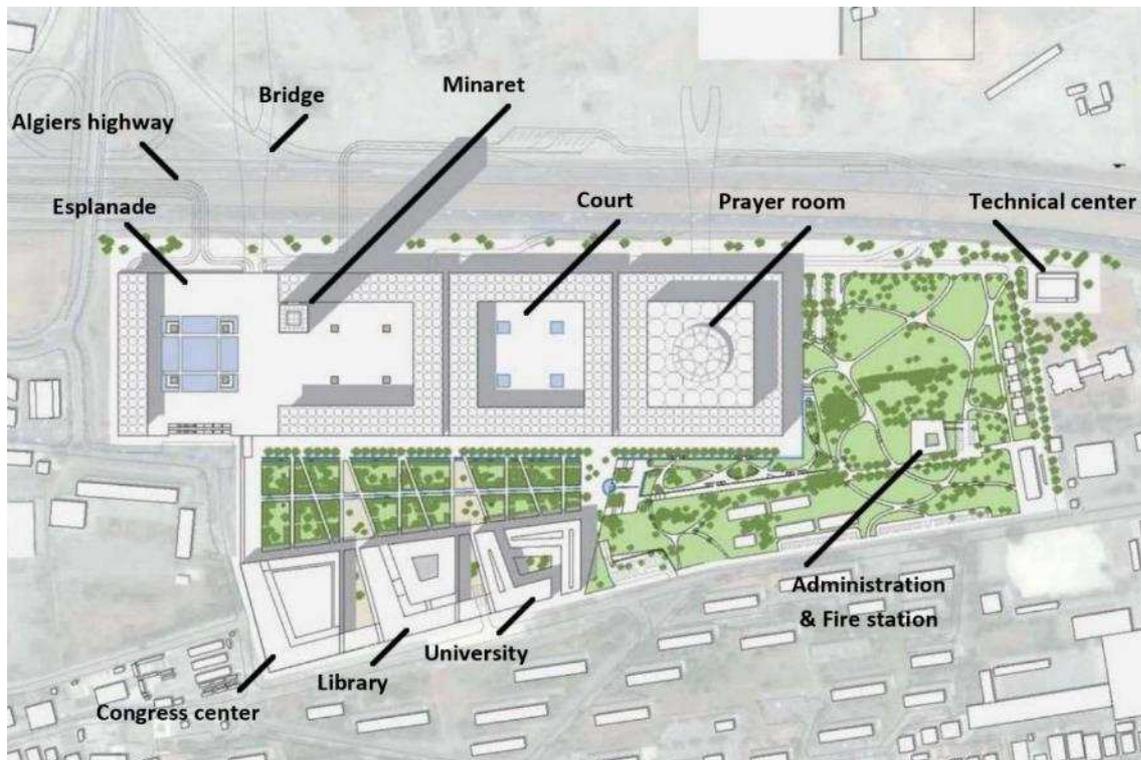


Fig. 1. The Great Mosque of Algiers [41].



Fig. 2. The Great Mosque of Algiers minaret [41].

A CCHP system is being designed for this Mosque complex. The design is based on the estimated monthly energy requirements. As shown in [Fig.3](#), the monthly electricity requirement is quite constant throughout the year. Although requirements for heating and cooling vary with weather conditions in different months. The cooling demand is higher in summer (from May to October) while the heat demand is higher in winter (from November to April). The CCHP system ought to be designed considering the capability to meet all these expected demands of the building for electricity, heat, and cold.

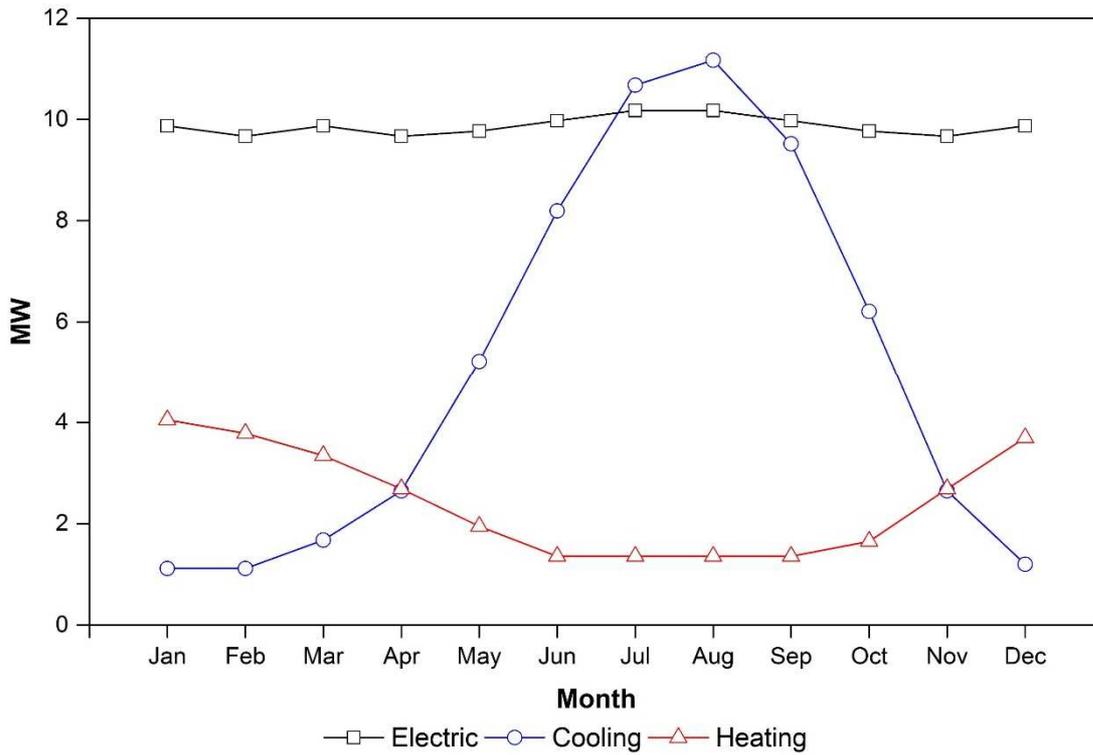


Fig. 3. Expected peak monthly utility demand [41].

In addition to the monthly loads, the hourly expected cooling demand profile is presented in Fig. 4. As can be observed, the demand for cooling is high between 8 a.m. and 9 p.m. while it is low from 9 p.m. to 8 a.m. The hourly consumption of electricity and heat, which are not presented in the figure, are estimated to have a similar trend as the cooling load during the day [42].

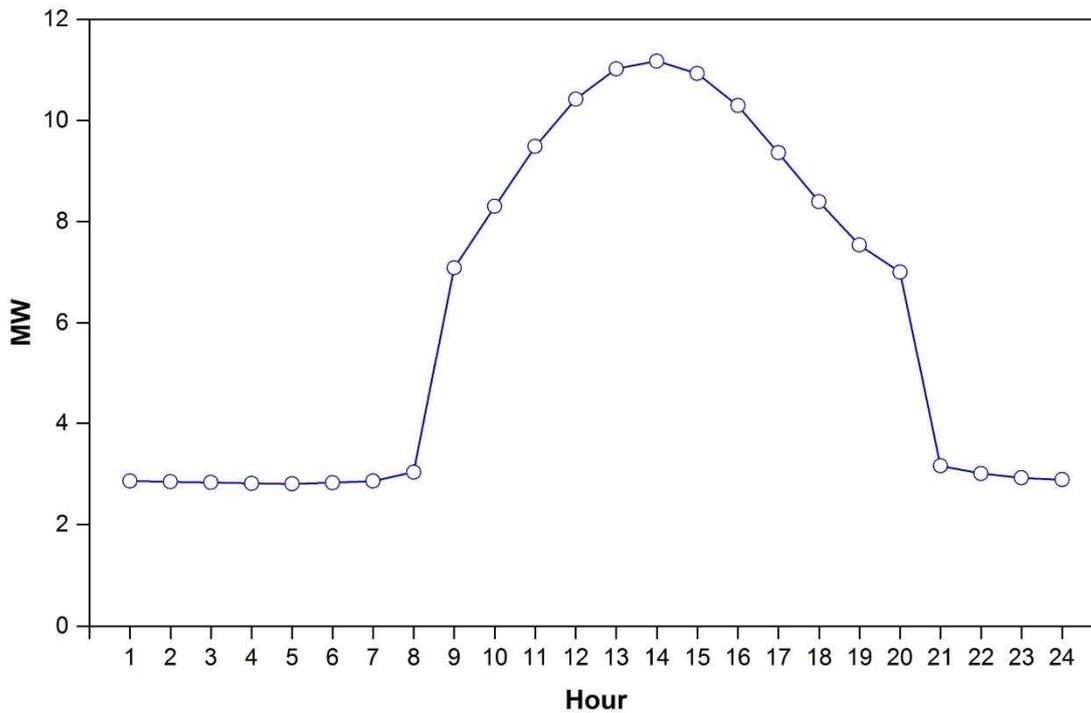


Fig. 4. Expected hourly cooling load [41].

The CCHP plant can be sized to import electricity from the grid when the site demand is higher than the generation capacity of the PGU. Based on the operating strategy used, the heat available from the CCHP plant, if not enough to fulfill the heat needs of the building, can be provided by a standby gas boiler.

The CCHP system can operate following two different strategies, electrical load following and heat load following. For the electrical load following strategy, the electrical output of PGU should be controlled to meet the building electrical load, any deficiency in heat production must be generated by a gas boiler and any excess heat production should be rejected to the environment. In the heat load following strategy, the output of the PGU unit should be controlled to meet the building heat demand first. This means that the electrical power output of the PGU will also vary and any deficiency will be made up from the national grid. In case that the electric power generation is greater than the building electrical demand, the surplus of electricity should be exported to the national grid.

Previous studies have demonstrated that the ELF strategy is capable of achieving higher energy and environmental performance compared to the TLF strategy. Therefore, we will be interested by the ELF and modified ELF strategies.

3. System design and strategy description

3.1. Separated production system

Heating demand can be satisfied by using the natural gas provided from the national grid as a source of thermal energy. Also, the cooling demand could be satisfied by using the electricity provided from the national grid in compression chillers. In this design, a compression chiller and heat boiler are used to provide heating and cooling demands as showed in Fig. 5. In order to meet all expected demand conditions, these components are sized according to the annual maximum thermal demands.

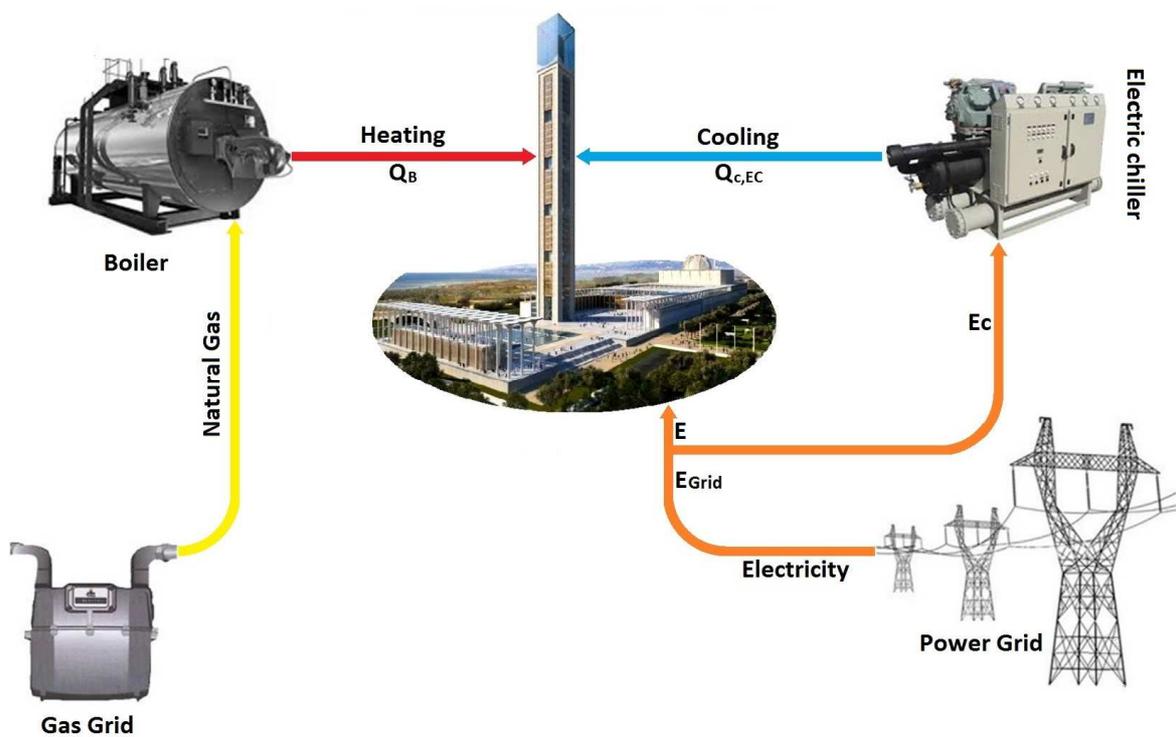


Fig. 5. Schematic of the SP system.

The total electrical energy consumed by SP system from the grid [17], E_{Grid}^{SP} , is

$$E_{Grid}^{SP} = E + E_{EC} \quad (1)$$

Where E is the building electric energy consumption the and E_{EC} is the electric energy consumed by the electrical chiller, which can be calculated as follows [17]

$$E_{EC} = \frac{Q_c}{COP_{EC}} \quad (2)$$

Where COP_{EC} is the coefficient of performance (COP) of the electrical chiller.

The total electricity consumption from grid can be converted to fuel consumption as follows [17]

$$F_{Grid} = \frac{E_{Grid}^{SP}}{\eta_e^{SP} \eta_{Grid}} \quad (3)$$

Where η_e^{SP} and η_{Grid} are the grid power generation efficiency and the grid distribution efficiency, respectively.

The fuel consumption from the heating system is calculated by

$$F_B = \frac{Q_h}{\eta_B} \quad (4)$$

Where Q_h is the heat demand, and η_B is the boiler efficiency. Therefore, the total fuel consumption can be calculated as

$$F_{SP} = \frac{E}{\eta_e^{SP} \cdot \eta_{Grid}} + \frac{Q_c}{COP_{Ec} \cdot \eta_e^{SP} \cdot \eta_{Grid}} + \frac{Q_h}{\eta_B} \quad (5)$$

3.2. Absorption chiller-only CCHP system under ELF strategy

Under ELF, the PGU generates electricity as much possible E_{PGU}^{MAX} . If the electrical load (E) is higher than the maximum power generation capacity of PGU, the electric deficiency of the building is covered by the grid. The PGU uses natural gas as fuel and generates electricity to the building. The high-temperature waste heat of PGU is recovered to support the thermal load for cooling and heating. For the absorption chiller-only CCHP system (Fig. 6), a boiler is used to generate additional heat (Q_B) when the recovered heat (Q_{Rec}) is not able to meet the cooling load (Q_c) and the heating load (Q_h). In this case, the absorption chiller provides the totality of cooling load by consuming more heat from the boiler [11].

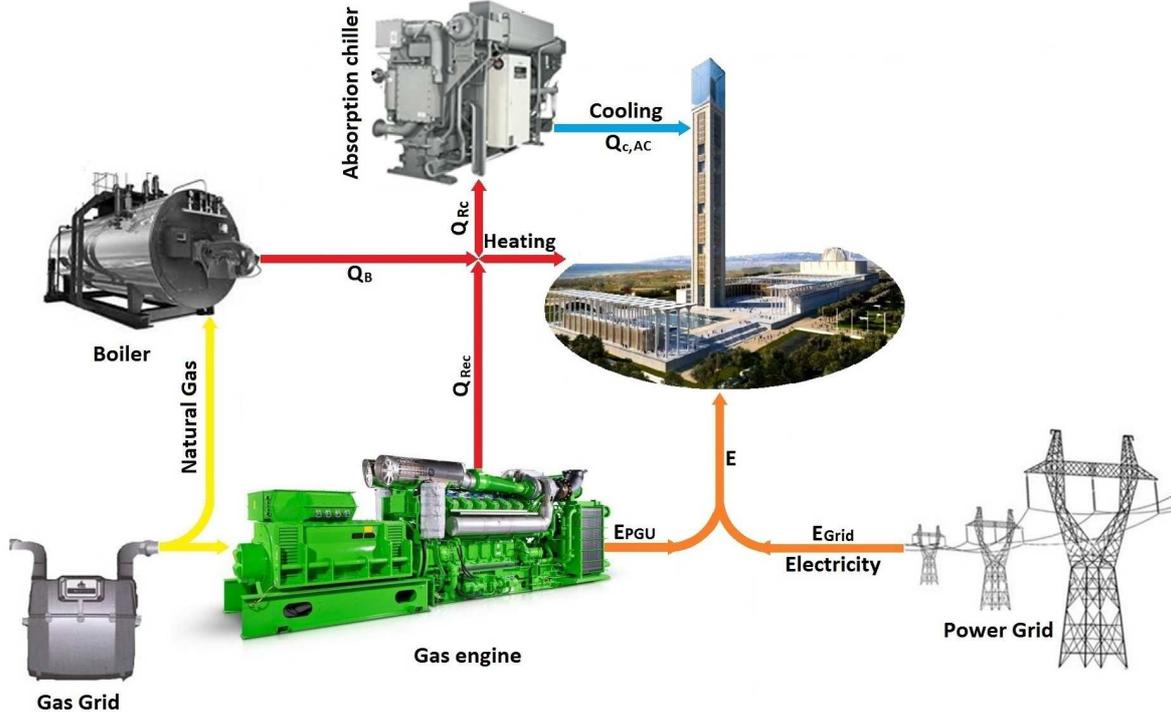


Fig.6. Schematic of the Absorption chiller-only CCHP system (System I).

The electrical energy balance in System I is [11]:

$$E_{PGU} = \begin{cases} E & , E < E_{PGU}^{MAX} \\ E_{PGU}^{MAX} & , E \geq E_{PGU}^{MAX} \end{cases} \quad (6)$$

$$E_{Grid} = \begin{cases} 0 & , E < E_{PGU}^{MAX} \\ E - E_{PGU}^{MAX} & , E \geq E_{PGU}^{MAX} \end{cases} \quad (7)$$

Where E is the building electric demand, E_{Grid} is the electricity supplied by the national grid to the CCHP system, E_{PGU} is the generated electricity by power generation unit (PGU) and E_{PGU}^{MAX} is the maximum capacity of power generation unit.

It is possible to calculate the PGU fuel consumption (F_{PGU}) as follow [11]:

$$F_{PGU} = \frac{E_{PGU}}{\eta_e} \quad (8)$$

Where η_e is the PGU electrical efficiency.

The recovered heat Q_{Rec} can be calculated as

$$Q_{Rec} = F_{PGU} \times \eta_{Rec} \times (1 - \eta_e) \quad (9)$$

Where η_{Rec} is the heat recovery system efficiency.

The heat balance between the cooling and the heating systems is

$$Q_{Rec} + Q_B = Q_{Rc} + Q_h \quad (10)$$

Where Q_B is the boiler's additional heat, Q_{Rc} and Q_h respectively are the heats supplied to the absorption chiller and the heating system.

The heat consumed by the absorption chiller can be calculated by

$$Q_{Rc} = \frac{Q_c}{COP_{AC}} \quad (11)$$

Where COP_{AC} is the absorption chiller COP .

The supplementary fuel consumed by the boiler, F_B , can be calculated as [11]:

$$F_B = \frac{Q_{Rc} + Q_h - Q_{Rec}}{\eta_B} \quad (12)$$

Therefore, the fuel consumption, F^{CCHP} , is calculated as

$$F^{CCHP} = F_{PGU} + F_{Grid} + F_B = \frac{E_{PGU}}{\eta_e} + \frac{E_{Grid}}{\eta_e^{SP} \cdot \eta_{Grid}} + \frac{Q_B}{\eta_B} \quad (13)$$

3.3. Hybrid chiller CCHP system

The arrangement of the hybrid chiller CCHP system is illustrated in Fig. 7. Under ELF, the PGU generates electricity as much possible E_{PGU}^{MAX} if the electrical charge (E) is higher than the maximum power generation capacity of PGU, while the missing electric energy of the building is covered by the grid. The electrical output of the PGU (E_{PGU}) and the grid electricity consumption (E_{Grid}) depend on the amount of electricity required for the building (E) and also the electric chiller (E_{Ec}).

To provide supplementary electric cooling, the PGU must increase the power generation. As the PGU power output increases, so does the heat output, leading to additional heat available to be used in absorption cooling and building heating. This causes lower demand for electric cooling and boilers heating [6].

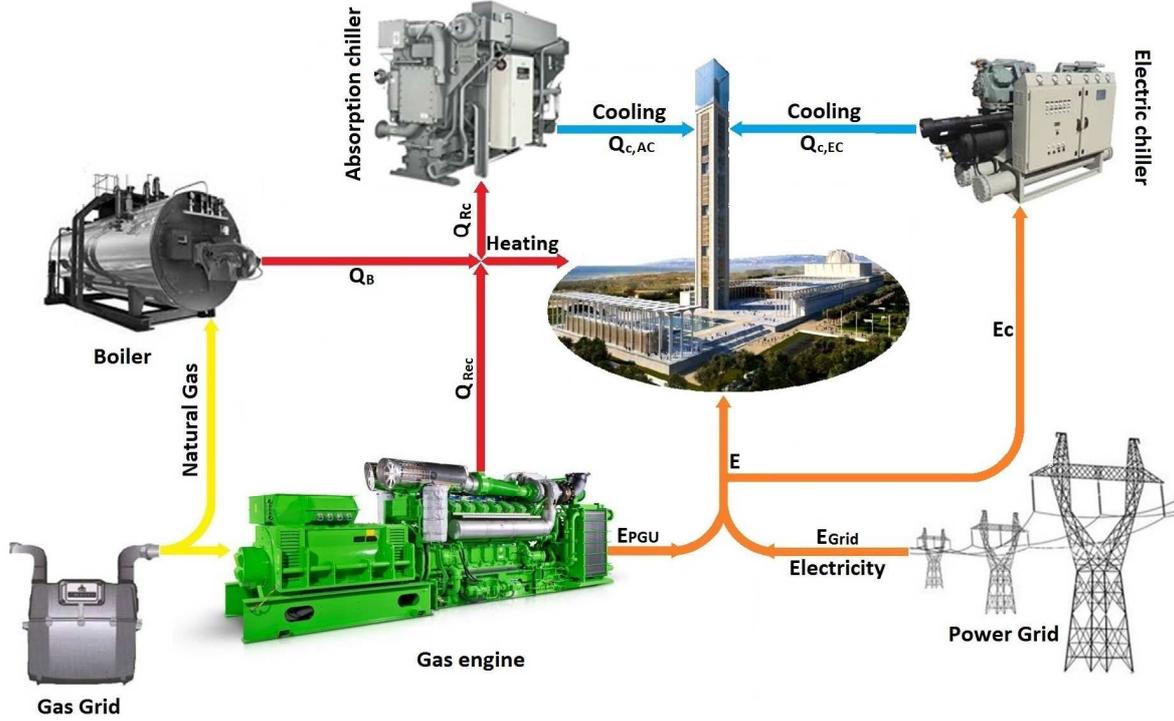


Fig.7. Schematic of the hybrid chiller CCHP system (System II).

3.3.1. The electric load following (ELF)

If the recovered heat (Q_{Rec}) does not completely satisfy the building needs, i.e. the heating load (Q_h) and the additional heat required for the absorption chillers (Q_{RC}), a boiler should be used to produce more heat (Q_B). Moreover, when the absorption chiller does not satisfy cooling requirements, supplementary cold is generated from the electric chiller by consuming more electricity. The detailed model of this strategy is described as follows [6]:

$$E_{PGU} = \begin{cases} E + E_{Ec} & , E + E_{Ec} < E_{PGU}^{MAX} \\ E_{PGU}^{MAX} & , E + E_{Ec} \geq E_{PGU}^{MAX} \end{cases} \quad (14)$$

$$E_{Grid} = \begin{cases} 0 & , E + E_{Ec} < E_{PGU}^{MAX} \\ E + E_{Ec} - E_{PGU}^{MAX} & , E + E_{Ec} \geq E_{PGU}^{MAX} \end{cases} \quad (15)$$

$$F_{PGU} = \frac{E_{PGU}}{\eta_e} \quad (16)$$

And the recovered heat Q_{Rec} is calculated as

$$Q_{Rec} = F_{PGU} \times \eta_{Rec} \times (1 - \eta_e) \quad (17)$$

The heat consumed by the absorption chiller can be calculated as

$$\left(\frac{Q_c}{\eta_{AC}} \right) \quad , Q_c < Q_{c,AC}^{MAX} \quad (18)$$

$$, Q_c \geq Q_{c,AC}^{MAX}$$

Where $Q_{c,AC}^{MAX}$ is the absorption chiller capacity.

And the heat produced by the boiler is calculated as

$$Q_B = \begin{cases} 0 & , Q_{Rec} \geq Q_{Rc} + Q_h \\ Q_{Rc} + Q_h - Q_{Rec}, & , Q_{Rec} < Q_{Rc} + Q_h \end{cases} \quad (19)$$

And the cold produced by the electric chiller is calculated as

$$Q_{c,EC} = \begin{cases} 0 & , Q_c < Q_{c,AC}^{MAX} \\ Q_c - Q_{c,AC}^{MAX} & , Q_c \geq Q_{c,AC}^{MAX} \end{cases} \quad (20)$$

And the electric energy consumed by the electric chiller is expressed as

$$E_{Ec} = \frac{Q_{c,EC}}{COP_{EC}} \quad (21)$$

In this configuration the fuel consumption of the system is calculated as

$$F^{CCHP} = F_{PGU} + F_B + F_{Grid} = \frac{E_{PGU}}{\eta_e} + \frac{E_{Grid}}{\eta_e^{SP} \cdot \eta_{Grid}} + \frac{Q_B}{\eta_B} \quad (22)$$

3.3.2. The modified electric load following (MELF)

In this strategy to satisfy the heating and cooling requirements in the building, the recovered heat (Q_{Rec}) is used primarily for heating (Q_h) and, secondly, for absorption cooling (Q_{Rc}). If the recovered heat is unable to satisfy the heating load (Q_h), additional heat should be produced by an auxiliary boiler. In this case, the electric chiller delivers the whole cooling load by consuming more electric power [21,28] :

The electrical energy balance is expressed as

$$E_{PGU} = \begin{cases} E + E_{Ec} & , E + E_{Ec} < E_{PGU}^{MAX} \\ E_{PGU}^{MAX} & , E + E_{Ec} \geq E_{PGU}^{MAX} \end{cases} \quad (23)$$

$$E_{Grid} = \begin{cases} 0 & , E + E_{Ec} < E_{PGU}^{MAX} \\ E + E_{Ec} - E_{PGU}^{MAX} & , E + E_{Ec} \geq E_{PGU}^{MAX} \end{cases} \quad (24)$$

the PGU fuel consumption (F_{PGU}) is calculated as follow

$$F_{PGU} = \frac{E_{PGU}}{\eta_e} \quad (25)$$

And the recovered heat Q_{Rec} is calculated as

$$Q_{Rec} = F_{PGU} \times \eta_{Rec} \times (1 - \eta_e) \quad (26)$$

The recovered heat (Q_{Rec}) is used primarily for heating (Q_h) and then for absorption cooling (Q_{RC}) in order to meet the heating and cooling loads in the building. As a result, the relationship between Q_{Rec} , Q_h and Q_{RC} can be expressed as

$$Q_{RC} = \begin{cases} Q_{Rec} - Q_h & , Q_{Rec} > Q_h \\ 0 & , Q_{Rec} \leq Q_h \end{cases} \quad (27)$$

If the recovered heat is not sufficient to satisfy the heating load (Q_h), the gas boiler produces additional heat. In this case, the electric chiller supplies the entire cooling load.

$$Q_B = \begin{cases} 0 & , Q_{Rec} > Q_h \\ Q_h - Q_{Rec} & , Q_{Rec} \leq Q_h \end{cases} \quad (28)$$

We introduce new parameter α , which is the maximum cold that can be produced by absorption, using the residual heat that we get from the recovered heat after the subtraction of the required heat for heating ($Q_{Rec} - Q_h$).

$$\alpha = \begin{cases} (Q_{Rec} - Q_h) \times COP_{Ac} & , Q_{Rec} > Q_h \\ 0 & , Q_{Rec} \leq Q_h \end{cases} \quad (29)$$

Then if α is less than absorption chiller capacity, the cold produced by absorption is equal to α . Instead, if α is bigger than the absorption chiller capacity, the cold produced by absorption chiller is equal to the maximum capacity of this latter.

$$Q_{c,Ac} = \begin{cases} \alpha & , \alpha < Q_{c,Ac}^{MAX} \\ Q_{c,Ac}^{MAX} & , \alpha \geq Q_{c,Ac}^{MAX} \end{cases} \quad (30)$$

If the absorption cooling cannot meet the cooling load, all the residual cooling load should be provided by the electrical chiller. In this case, the cold produced by the electric chiller is expressed as

$$Q_{c,Ec} = Q_c - Q_{c,Ac} \quad (31)$$

And the electric energy consumed by the electric chiller is expressed as

$$E_{Ec} = \frac{Q_{c,Ec}}{COP_{Ec}} \quad (32)$$

And the fuel consumption of the system is calculated as follow

$$F^{CCHP} = F_{PGU} + F_B + F_{Grid} = \frac{E_{PGU}}{\eta_e} + \frac{E_{Grid}}{\eta_e^{SP} \cdot \eta_{Grid}} + \frac{Q_B}{\eta_B} \quad (33)$$

More details regarding the MELF strategy are described in references [21,28].

3.3.3. The new modified electric load following (NELF)

In the new suggested strategy, the boiler is only operated if the recovered heat does not satisfy the heating demand or if the electric chiller does not fulfill the cooling requirements of the building. Therefore, If the electric chiller is unable to fully satisfy the cooling requirements (Q_c), the absorption chiller provides additional cooling ($Q_{c,AC}$) by using supplementary heat from the boiler.

$$E_{PGU} = \begin{cases} E + E_{Ec} & , E + E_{Ec} < E_{PGU}^{MAX} \\ E_{PGU}^{MAX} & , E + E_{Ec} \geq E_{PGU}^{MAX} \end{cases} \quad (34)$$

$$E_{Grid} = \begin{cases} 0 & , E + E_{Ec} < E_{PGU}^{MAX} \\ E + E_{Ec} - E_{PGU}^{MAX} & , E + E_{Ec} \geq E_{PGU}^{MAX} \end{cases} \quad (35)$$

$$F_{PGU} = \frac{E_{PGU}}{\eta_e} \quad (36)$$

$$Q_{Rec} = F_{PGU} \times \eta_{Rec} \times (1 - \eta_e) \quad (37)$$

- In case that the recovered heat is less than or equal to heat load ($Q_{Rec} \leq Q_h$), the cooling load should be covered by the electric chiller first

$$Q_{c,Ec} = \begin{cases} Q_c & , Q_c < Q_{c,Ec}^{MAX} \\ Q_{c,Ec}^{MAX} & , Q_c \geq Q_{c,Ec}^{MAX} \end{cases} \quad (38)$$

And if the cooling load is higher than electric chiller capacity ($Q_{c,Ec}^{MAX}$), the absorption chiller should provide the residual cooling load. In this case, the heat required for cooling is expressed as

$$Q_{Rc} = \frac{Q_c - Q_{c,Ec}}{COP_{Ac}} \quad (39)$$

- In case the recovered heat is larger than heat load ($Q_{Rec} > Q_h$), the cooling load should be provided first by the absorption chiller, by using the residual thermal energy that we get from the recovered heat after the subtraction of the required energy for heating. The expression of α , which is the maximum cold that can be produced by absorption, will be

$$\alpha = (Q_{Rec} - Q_h) \times COP_{Ac} \quad (40)$$

If α is greater or equal to absorption chiller capacity ($Q_{c,AC}^{MAX} \leq \alpha$), then the cold produced by the electric chiller is expressed as

$$Q_{c,Ec} = \begin{cases} 0 & , Q_c \leq Q_{c,AC}^{MAX} \\ Q_c - Q_{c,AC}^{MAX} & , Q_c > Q_{c,AC}^{MAX} \end{cases} \quad (41)$$

If α is less than absorption chiller capacity ($Q_{c,Ac}^{MAX} > \alpha$), then the cold produced by the electric chiller is expressed as

$$Q_{c,Ec} = \begin{cases} 0 & , Q_c \leq \alpha \\ C - \alpha & , \alpha < Q_c < Q_{c,Ec}^{MAX} + \alpha \\ Q_{c,Ec}^{MAX} & , Q_{c,Ec}^{MAX} + \alpha \leq Q_c \end{cases} \quad (42)$$

In case the cold produced by the absorption chiller, based on the residual heat (α), and by the electric chiller ($Q_{c,Ec}^{MAX}$) is less than cooling load, the absorption chiller provides additional cooling ($Q_{c,Ac}$) by consuming supplementary heat from the boiler.

The heat consumed by the cooling system can be calculated as

$$Q_{Rc} = \frac{Q_c - Q_{c,Ec}}{COP_{Ac}} \quad (43)$$

And the thermal energy produced by the boiler can be expressed as

$$Q_B = Q_h + Q_{Rc} - Q_{Rec} \quad (44)$$

In addition, the electric energy consumed by the electric chiller is expressed as

$$E_{Ec} = \frac{Q_{c,Ec}}{COP_{Ec}} \quad (45)$$

And the fuel consumption of the system is calculated as follow

$$F^{CCHP} = F_{PGU} + F_B + F_{Grid} = \frac{E_{PGU}}{\eta_e} + \frac{E_{Grid}}{\eta_e^{SP} \cdot \eta_{Grid}} + \frac{Q_B}{\eta_B} \quad (46)$$

4. Multi-objective optimization

In multi-objective optimization problems, there is usually no viable solution capable of maximizing or minimizing all objective functions at the same time. Therefore, attention is then given to Pareto's optimal solutions, that are not dominated by any other solutions and cannot be improved with regard to any objective without weakening at least one objective. The Pareto optimal set is defined as the set of all non-dominated solutions, and the associated objective function values are called the Pareto frontier. The Pareto frontier is limited by a nadir objective vector z^{nadir} , and an ideal objective vector z^{ideal} , which define the lower and the upper bounds of the optimum Pareto solution's objective function [43], respectively. All the elements mentioned above are illustrated in fig. 8, which shows the Pareto front of the multi-objective optimization of the two objective functions f_1 and f_2 .

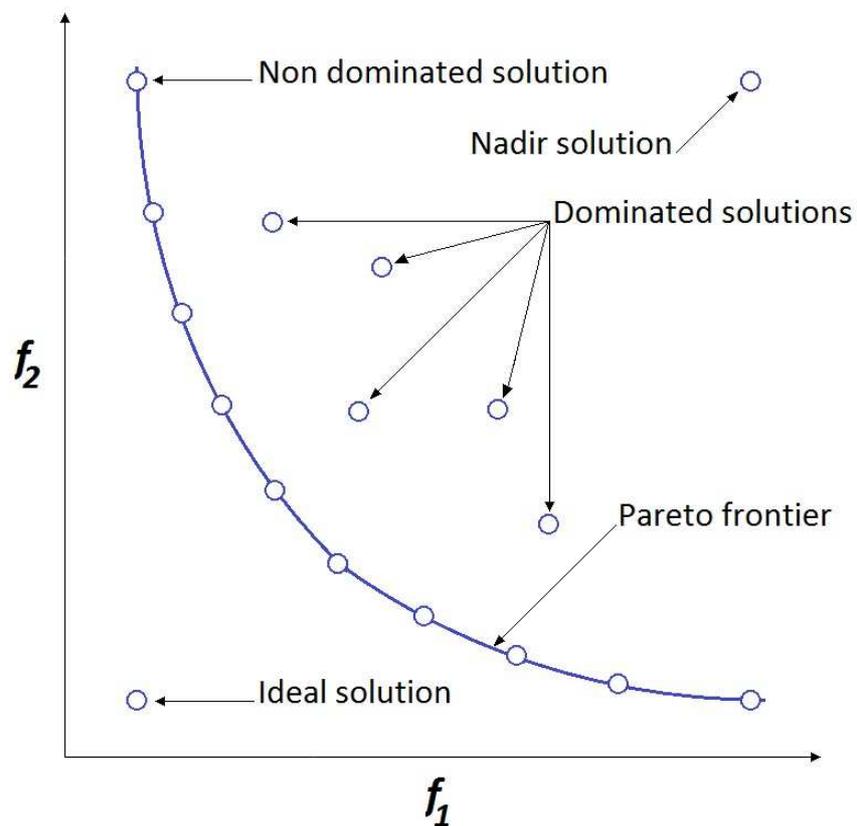


Fig. 8. Pareto frontier of a multi-objective optimization.

Genetic and evolutionary algorithms (GEAs) were proposed by John Holland in his pioneering work on the field, as a repetitive, stochastic search method to find optimal solutions by mimicking in a simplified way the theory of biological evolution [44]. Multi-objective

optimization using a genetic algorithm is employed in this study, based on the well-known NSGA-II algorithm of Deb et al [40], to achieve the Pareto optimal set by the seven steps described in Fig. 9. In the NSGA-II evolutionary process, the initial parent population is first created and sorted on the basis of two criteria which are rank and crowding distance. Next, the chosen individuals by a tournament selection would be deposited in an intermediate mating pool, crossover, and mutation processes will be used to produce the child populations. Then, the old set of solutions and the newly generated solutions are combined to make a larger size of population, and fitness values are attributed to all individuals by non-dominated sorting. Finally, individuals with the best fitness values are chosen by elitist sorting, and they become the parent population. These steps are reproduced until the maximum number of generations is reached. Once NSGA-II finishes processing, the approximate Pareto front of multi-objective space would be generated by the non-dominated solutions of the final population.

Therefore, to optimize the CCHP systems, the technical and economic parameters are listed in Tables 1, 2, and 3, respectively. Table 4 lists the input parameters of the algorithm NSGA-II [38]. The population and the maximum number of generations were set to 500 and 600, respectively, to balance between more accurate optimal results and less optimization time. Selecting the mutation probability and crossover probability is crucial to find the global optimal solutions. The mutation operators are used mainly to provide exploration and crossover operators are usually used to guide the population to converge on the good solutions. In addition, a high crossover probability value can improve the search process for complicated search spaces. on the other hand, the probability of mutations normally must be maintained very low. Alternatively, convergence can be delayed needlessly [45].

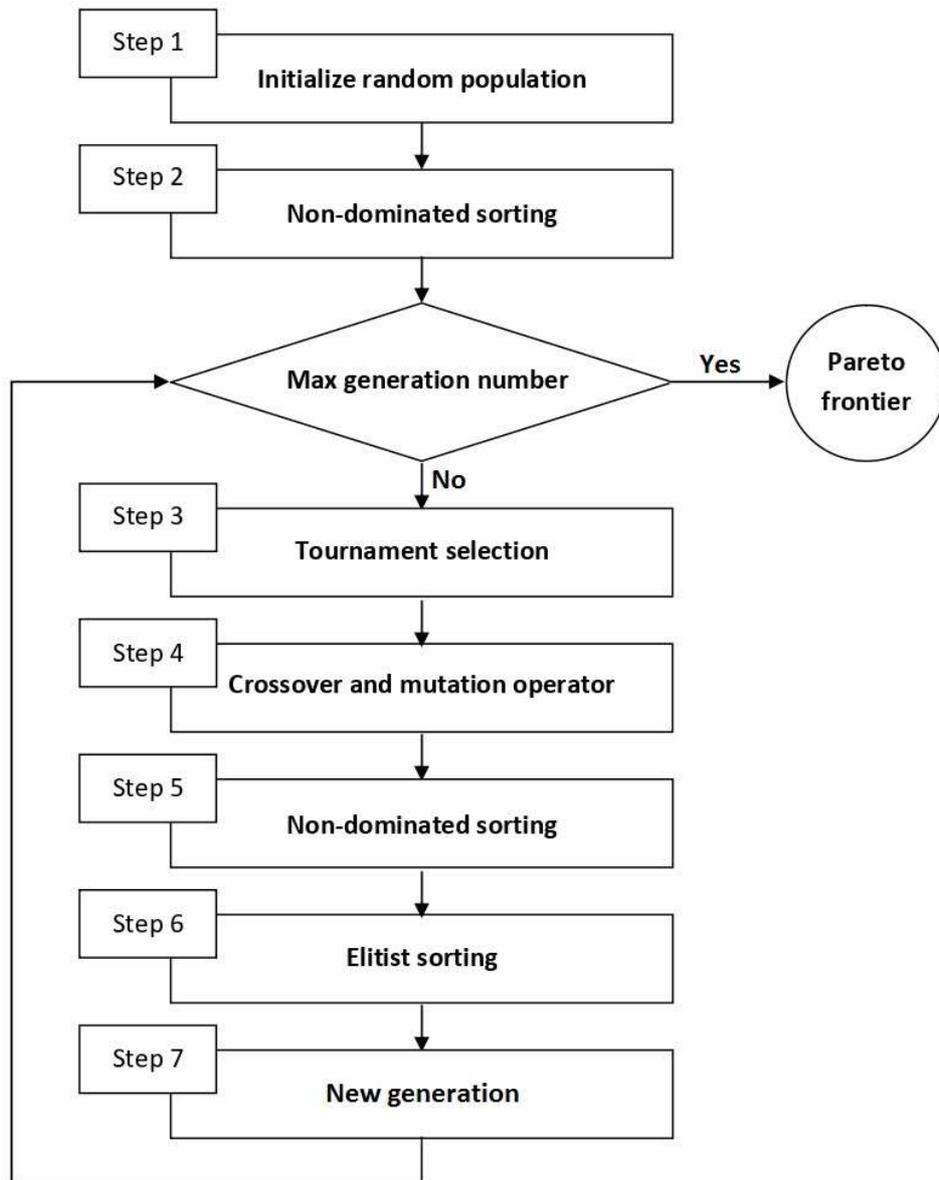


Fig. 9. Flow chart of NSGA-II algorithm.

Table 1

The variables of SP system and CCHP system.

System	Variable	Value	Ref
PGU	Electric efficiency (%)	40.2	
	Thermal efficiency (%)	75.6	
Electric chiller	COP	5.2	
Absorption chiller	COP	0.76	
Gas boiler	Efficiency (%)	95	
Grid	Generation efficiency (%)	43.65	[46]
	Transmission efficiency (%)	82.87	[47]
CO ₂ emission	Natural gas (g/kWh)	220	[6]
	Electricity from grid (g/kWh)	625	[48]

Table 2

Unit cost of the equipment in CCHP and SP systems.

Component	Investment cost (€/kW)
PGU	750
Absorption chiller	136
Electric Chiller	133
Gas boiler	64

Table 3

Natural gas and electricity prices under time-of-use tariff in Algeria.

	Natural gas	Electricity (6:00-17:00,21:00-22:30)	Electricity (17:00-21:00)	Electricity (22:30-6 :00)
Unit price (€/kWh)	0.0018	0.0156	0.0703	0.0083

Table 4

Parameter values used in NSGA-II algorithm.

Tuning parameter	Value
Population size	500
Maximum number of generation	600
Probability of crossover	0.9
Probability of mutation	0.1
Distribution index of crossover operator	20
Distribution index of mutation operator	20
Tournament size	2

4.1. Definition of objective functions

In this multi-objective optimization, three objective functions are considered [6,49]: primary energy consumption (to be minimized), annual total cost (to be minimized) and carbon dioxide emissions (to be minimized). Therefore, the objective functions have been formulated as follows:

4.1.1. Energetic criterion

Primary energy consumption (*PEC*) is the most important and consistent indicator reflecting the CCHP system's operational efficiency. In addition, *PEC* has a strong relationship with environmental and economic performance. So, this criterion is used first.

$$PEC = F_{PGU} + F_B + F_{Grid} \quad (47)$$

4.1.2. Economic criterion

The annual total cost (ATC), including the annual cost of capital, the annual cost of operation and maintenance, and the annual cost of energy is determined as follows:

$$ATC = C_{Inv} + C_{O\&M} + C_{NG} + C_{GE} \quad (48)$$

$$ATC = R \times \sum_1^l N_k C_k + \epsilon \times \sum_1^l N_k C_k + \sum_{i=1}^{365} \sum_{j=1}^{24} (E_{ij,GE} \times C_{ij,e} + F_{ij,f} \times C_{ij,NG}) \quad (49)$$

Where C_{Inv} , $C_{O\&M}$, C_{NG} and C_{GE} are the annual equipment investment cost, operation & maintenance cost, natural gas cost, and grid electricity cost, respectively. While N and C are the installed power of the equipment and the initial capital cost of each type of equipment in euro (1 € = 132 DA), respectively. l is the number of equipment, $C_{ij,GE}$ and $C_{ij,NG}$ are the hourly energy tariffs of electricity and natural gas, respectively. The annual operation and maintenance cost of equipment is considered to be as 6% ($\epsilon=0.06$) of their investment cost [50].

The capital recovery factor, R , is defined as:

$$R = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (50)$$

Where i is the rate of interest and n is the equipment's service life ($i=6\%$ and $n=20$ years). while the values of i and n are considered to be equal to all types of equipment.

4.1.3. Environmental criterion

The emission conversion factors can be used to determine the amount of carbon dioxide emissions (CDE) as follows:

$$CDE = (F_{PGU} + F_B) \times \mu_{CO_2,NG} + E_{Grid} \times \mu_{CO_2,GE} \quad (51)$$

where $\mu_{CO_2,NG}$ and $\mu_{CO_2,GE}$ are the natural gas and grid emission conversion factors respectively.

4.2. Decision-making in multi-objective optimization

The decision-making process is necessary for multi-objective optimization problems to choose a final optimal solution from the possible solutions. The decision-making process

usually depends on engineering experience, the preferences and criteria taken by the decision-maker on which objective function would be of more importance. There are many methods for decision-making process in decision problems. For instance, Fuzzy, TOPSIS and LINMAP decision-making methods. These methods are usually used for selection of a final optimal solution from the Pareto frontier [51]. Decision-making has been applied in two phases in this paper. Firstly, as with multi-objective optimization, we get a set of optimal solutions, called the Pareto front. Consequently, there is not a single final optimal solution, like in the single-objective optimization problems. In the next phase of decision-making, one configuration should be chosen from all the feasible optimal configurations of the CCHP system located in the Pareto frontier. For this reason, three most recognized and common approaches of decision-making, namely Bellman-Zadeh fuzzy [52], LINMAP [53], and TOPSIS [54] decision methods were used. A brief description of these three methods is reported in [55]. Nevertheless, in this study, one strategy for the conventional CCHP system and three strategies for the CCHP system with hybrid chiller were optimized and for each, Pareto frontier has been obtained. Consequently, three optimal solutions were picked up from the Pareto frontier by using the three decision-making approaches, and a decision-making was needed to determine the final configuration of each CCHP system under the different strategies. Therefore, in this stage of decision-making the most economical optimal solution was adopted.

4.3. Performance indicators

To evaluate the energetic, economic and environmental performance of CCHP system in comparison to SP system, the following evaluation criteria are utilized.

4.3.1. Primary energy saving ratio

$$PESR = \frac{PEC^{SP} - PEC^{CCHP}}{PEC^{SP}} = 1 - \frac{PEC^{CCHP}}{PEC^{SP}} \quad (54)$$

PES is generally utilized to assess the fuel energy saving attained by CCHP system over SP system.

4.3.2. Annual Total Cost Saving Ratio

$$ATCSR = \frac{ATC^{SP} - ATC^{CCHP}}{ATC^{SP}} = 1 - \frac{ATC^{CCHP}}{ATC^{SP}} \quad (55)$$

The ratio between the annual CCHP system total cost and the annual SP system total cost is defined as the ATCS ratio.

4.3.3. Carbon dioxide emission reduction ratio

$$CDERR = \frac{CDE^{SP} - CDE^{CCHP}}{CDE^{SP}} = 1 - \frac{CDE^{CCHP}}{CDE^{SP}} \quad (56)$$

CDERR illustrates the environmental benefits gained through the use of CCHP system compared to SP system.

5. Results and discussion

The multi-objective optimization of the four CCHP systems resulted into four sets of Pareto fronts as shown in Fig. 10. The Pareto fronts of the CCHP systems have the same shape and the three objectives showed an interrelated relationship. When the PEC shows a decreasing trend and the CDE follows the same trend, while the ATC shows an upward trend. Tab. 5 summarizes the results and design parameters for all candidate solutions on Pareto fronts curves.

Fig. 10a and Table 5 show that, for absorption chiller CCHP based ELF, the maximum value of PESR and CDERR are 21.35% and 23.30% respectively, while the ATCSR is at its lowest value in this point with 2.79%. Conversely, while the ATCSR is at its highest value with 16.06%, the PESR and CDERR are at their lowest values in this point with 17.59% and 19.27% respectively.

In the hybrid chiller CCHP based ELF strategy, when PESR and CDERR are at their optimal solutions 22.53% and 24.45% respectively, ATCSR is at its lowest value -2.14% (Fig. 10b and Table 5). On the contrary, when ATCSR is at its optimal solution with 19.74%, PESR and CDERR are at their lowest values 20.00% and 21.60% respectively.

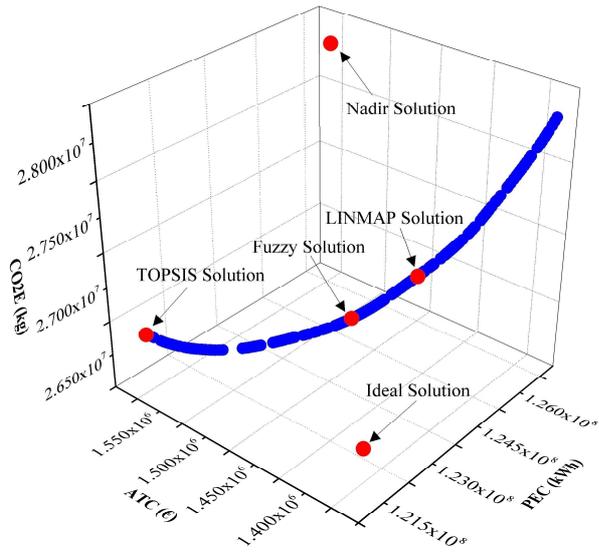
For the hybrid chiller CCHP based MELF strategy, when PESR and CDERR achieve their best values of 23.65% and 25.55% respectively, ATCSR reaches its lowest value of -9.98% (Fig. 10c and Table 5). Alternatively, when ATCSR hits its best value of 13.80%, PESR and CDERR are at their lowest values of 18.36% and 19.92% respectively.

In the same way, with the hybrid chiller CCHP based NELF, when the system hits its highest PESR and CDERR values of 23.65% and 25.55% respectively, the ACSR of the system is at its lowest value of 2.02% (Fig. 10d and Table 5). While, when the ACSR is at its highest value of 20.34%, both the PESR and CDERR drop to 21.1% and 22.65% respectively.

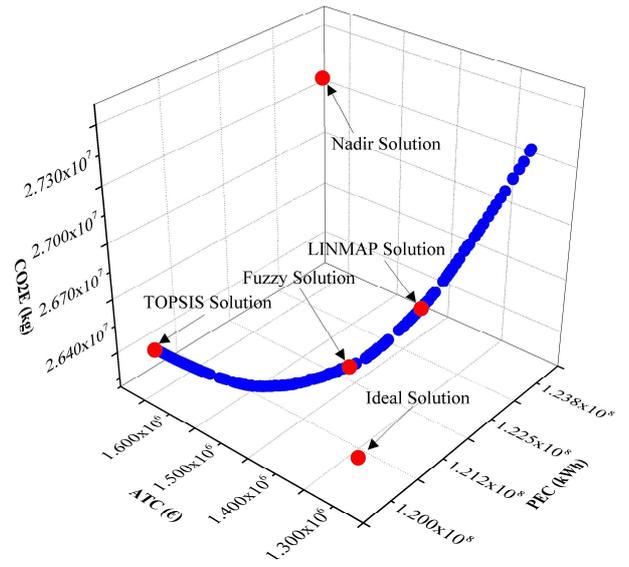
In addition, Fig. 10 shows that in the hybrid chiller CCHP based ELF and MELF strategies, if the CCHP system is optimized to save energy, there are no economic benefits in this case (ATCS is negative).

As illustrated in Fig. 10, it is not possible to obtain the maximum energetic and environmental performance simultaneously with the maximum economic performance.

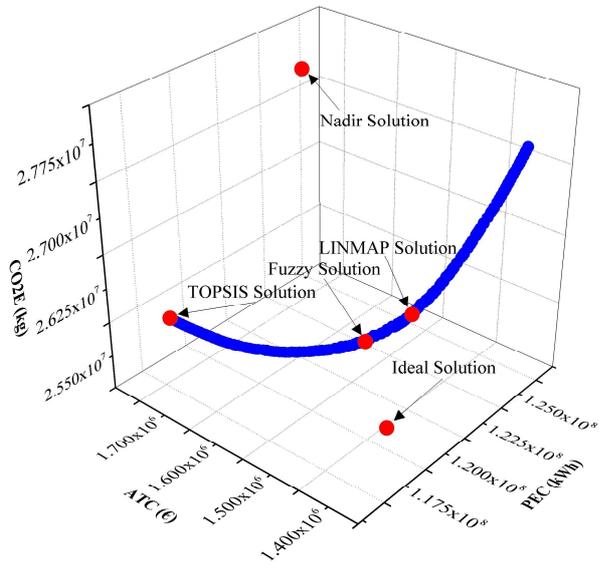
Consequently, in order to select the best feasible solutions on the Pareto fronts, a decision-making approach should be employed. In this fact, three most recognized and common approaches of decision-making, Bellman-Zadeh fuzzy, LINMAP, and TOPSIS decision methods were used in this study. Table 5 shows the characteristics of CCHP systems suggested by Fuzzy, LINMAP and TOPSIS decision-making approaches. The issue now is which decision-making optimal solution should be adopted. Table 5 and Fig. 10 are presented here to help us to decide between various decision-making methods. Fig. 10 shows that, LINMAP decision-making method lead to the highest ATCSR for all the CCHP systems followed by Fuzzy and TOPSIS decision-making methods, respectively. Consequently, the optimal solutions of LINMAP method appeared to be a more desirable final solutions in our case study. It should be mentioning that in general there is no decision-making method having superiority over other methods in all cases. In fact, different decision-making approaches are used to help decision-makers who choose the final solution based on their priority and experience. In this study, three decision-making approaches have been implemented and it was found that the LINMAP decision-making approach selects the final optimum solution that is more suitable to our criteria and preferences.



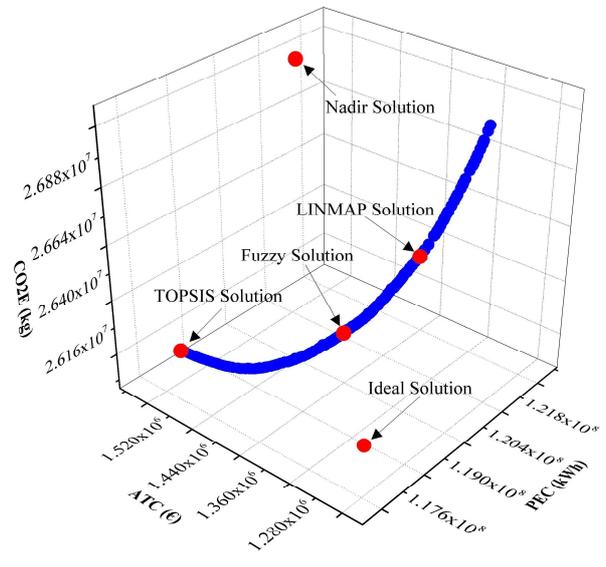
System I - ELF



System II - ELF



System II - MELF



System II - NELF

Fig. 10. Pareto frontier for triple objective (PEC,ATC,CDE) optimization of CCHP systems.

Table 5

Results and design parameters for the optimized systems selected from Pareto fronts.

	PGU (MW)	AC (MW)	EC (MW)	B (MW)	PEC (10 ⁷ kWh /year)	ATC (10 ⁵ € /year)	CDE (10 ⁶ kg /year)	PESR (%)	ACTSR (%)	CDERR (%)
SP System										
	-	-	11.173	4.0476	15.525	16.566	35.025	-	-	-
CCHP system under ELF										
Bellman–Zadeh Fuzzy Solution	8.342	11.173	-	6.471	12.376	14.540	27.265	20.28	12.23	22.15
LINMAP Solution	7.790	11.173	-	7.299	12.478	14.240	27.511	19.63	14.16	21.45
TOPSIS Solution	10.178	11.173	-	4.613	12.210	16.104	26.862	21.35	2.79	23.30
Single objective based on minimum PEC	10.178	11.173	-	4.613	12.210	16.104	26.862	17.59	16.05	19.27
Single objective based on minimum ATC	6.522	11.173	-	8.725	12.795	13.906	28.274	17.59	16.05	19.27
Single objective based on minimum CDE	10.178	11.173	-	4.613	12.210	16.104	26.862	21.35	2.79	23.30
Bellman–Zadeh Fuzzy Solution	-	-	-	-	12.210	13.906	26.862	21.35	16.05	23.30
Hybrid CCHP system under ELF										
Bellman–Zadeh Fuzzy Solution	8.303	5.855	5.318	1.499	12.106	14.038	26.681	22.02	15.26	23.82
LINMAP Solution	7.403	5.289	5.884	1.304	12.197	13.515	26.923	21.43	18.53	23.13
TOPSIS Solution	11.217	6.077	5.096	1.689	12.026	16.921	26.459	22.53	-2.14	24.45
Single objective based on minimum PEC	11.218	6.077	5.096	1.689	12.027	16.921	26.459	22.53	-2.14	24.45
Single objective based on minimum ATC	6.591	5.438	5.735	1.397	12.420	13.296	27.457	20.00	19.74	21.60
Single objective based on minimum CDE	11.218	6.077	5.096	1.689	12.027	16.921	26.459	22.53	-2.14	24.45
Ideal Solution	-	-	-	-	12.027	13.396	26.459	22.53	19.74	24.45
Hybrid CCHP system under MELF										
Bellman–Zadeh Fuzzy Solution	7.887	5.790	11.173	4.048	12.030	15.127	26.531	22.51	8.69	24.25
LINMAP Solution	7.136	5.117	11.173	4.048	12.138	14.672	26.808	21.82	11.55	23.46
TOPSIS Solution	10.764	8.172	11.173	4.048	11.853	18.220	26.076	23.65	-9.98	25.55
Single objective based on minimum PEC	10.764	8.172	11.173	4.048	11.853	18.220	26.076	23.65	-9.98	25.55
Single objective based on minimum ATC	6.561	1.404	11.173	4.048	12.675	14.280	28.047	18.36	13.80	19.92
Single objective based on minimum CDE	10.764	8.172	11.173	4.048	11.853	18.220	26.076	23.65	-9.98	25.55
Ideal Solution	-	-	-	-	11.853	14.280	26.076	23.65	13.80	25.55
Hybrid CCHP system under NELF										
Bellman–Zadeh Fuzzy Solution	8.487	6.378	4.795	0.205	11.962	14.028	26.355	22.95	15.32	24.75
LINMAP Solution	7.508	5.483	5.690	0.129	120.80	13.432	26.660	22.19	19.03	23.88
TOPSIS Solution	10.757	8.162	3.011	0	11.853	16.232	26.076	23.65	2.02	25.55
Single objective based on minimum PEC	10.757	8.162	3.011	0	11.853	16.232	26.076	23.65	2.02	25.55
Single objective based on minimum ATC	6.526	4.546	6.627	0	12.249	13.196	27.089	21.10	20.34	22.65
Single objective based on minimum CDE	10.757	8.162	3.011	0	11.853	16.232	26.076	23.65	2.02	25.55
Ideal Solution	-	-	-	-	11.853	13.196	26.076	23.65	20.34	25.55

Fig. 11 illustrates the primary energy consumption structures and primary energy saving ratio (PESR) of the optimized CCHP systems and SP system. According to the figure, the energy consumption is reduced for all examined CCHP systems. Moreover, the hybrid chiller CCHP system based NELF, the hybrid chiller CCHP system based MELF strategy and the hybrid chiller CCHP system based ELF have lower primary energy consumption than absorption chiller CCHP system based ELF strategy respectively.

The gas boilers in the systems II based MELF, systems II based NELF and systems II based ELF consume less natural gas and produce less thermal energy than that in System I, respectively. Thus, systems II based MELF, based ELF and based NELF, consume extra grid electricity for electric chiller and extra natural gas for PGU to compensate the thermal energy. However, system II following MELF seems to consume a bit more grid electricity than others strategies, because of its high demand of electricity for its electric chiller. Comparing all the CCHP systems, Hybrid chiller CCHP systems have a higher PESR compared to CCHP system with absorption chiller only due to the high COP of electric chiller (5.2) and the low COP of the absorption chiller (0.76) that requires undesirably high boiler gas consumption to serve large cooling and heating loads.

From the technical viewpoint, the CCHP system with hybrid chiller is recognized to be the most suitable technique for the Mosque complex application, with satisfying energy savings. On the other hand, from the viewpoint of design and management, all examined CCHP systems have higher PESR than that SP System.

Nevertheless, the PESR value of the NELF hybrid chiller CCHP system is higher than those of MELF and ELF. The reason for this difference is caused not only by the mode of operation but also by the prime mover size. It can be mentioned that the capacity of PGU in the system-II following NELF strategy is bigger than those of ELF and MELF strategies, respectively. This leads to less electricity consumption from the grid and more heat production to feed the building requirement in the NELF strategy than other strategies. In general, from an energetic point of view, NELF, MELF, and ELF based CCHP systems are suitable strategies for the Mosque complex examined in the current case study. Among the examined four design and management options, the hybrid chiller CCHP system based NELF strategy achieve the best energy performance, followed by the hybrid chiller CCHP system based MELF strategy,

the hybrid chiller CCHP system based ELF and absorption chiller CCHP system based ELF strategy.

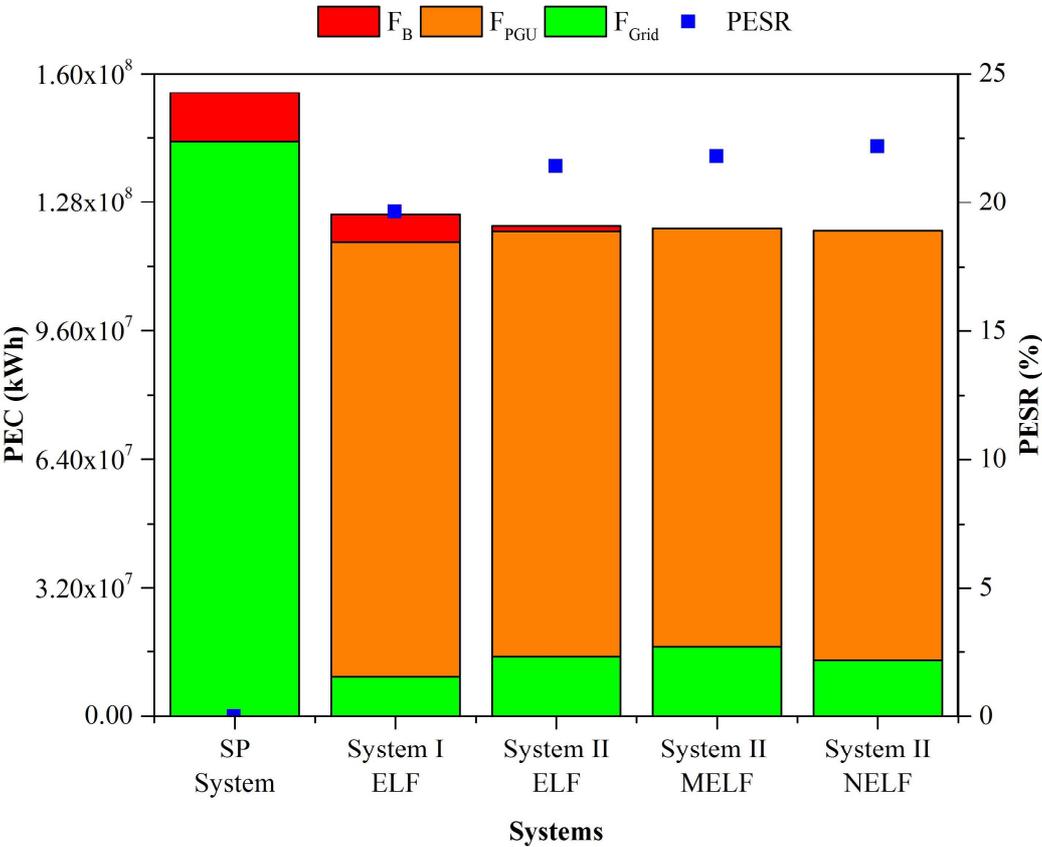


Fig. 11. Annual PEC and PESR of the reference and CCHP systems.

In this study, economic parameters for comparing the CCHP systems are annual investment cost, operating and maintenance cost, natural gas cost and grid electricity cost. Fig. 12 shows these four parameters. As shown in Fig. 12, the lowest annual investment and operation costs are obtained for system II based ELF strategy and system II based NELF strategy, due to the low size and investment cost of the boiler. On the other hand, the highest annual investment and operation costs are observed for system II based MELF strategy and system I based ELF strategy. This can be explained by the over sizing of the electric chiller and boiler in the system II based MELF strategy and the high capacities of the absorption chiller and the boiler in the system I based ELF strategy. In different types of chillers, the COP of the electric chiller is higher than the absorption chiller, so system II have the lowest natural gas consumption costs due to the higher impact of electric chiller COP. In addition, system I

presents the lowest grid electricity consumption cost due to the high capacity of PGU and the absence of an electric chiller in this strategy.

Moreover, Fig. 12 shows the ATC and ATCSR for various optimized options. Typically, all CCHP systems reach positive ATCSR under different designs and strategies. This implies that from an economic point of view, it is possible to implement the CCHP system for the studied Mosque complex. As for the relative comparison, with different management strategies, the hybrid chiller CCHP system under the NELF strategy offers better economic performance than the other systems, due to its low investment and fuel consumption costs. Although the hybrid chiller CCHP system under MELF has relatively high investment cost, its ATC is larger than other CCHP systems. This is mainly due to the relatively high annual investment cost caused by the oversizing of the CCHP system devices under this strategy. Therefore, from an economic point of view, the CCHP system can be considered as an attractive energy supply system, especially under hybrid chiller design, for the Mosque complex in the current situation. This is mainly the result of the relatively low capital cost of the CCHP system devices and the relatively high electricity price compared to natural gas price.

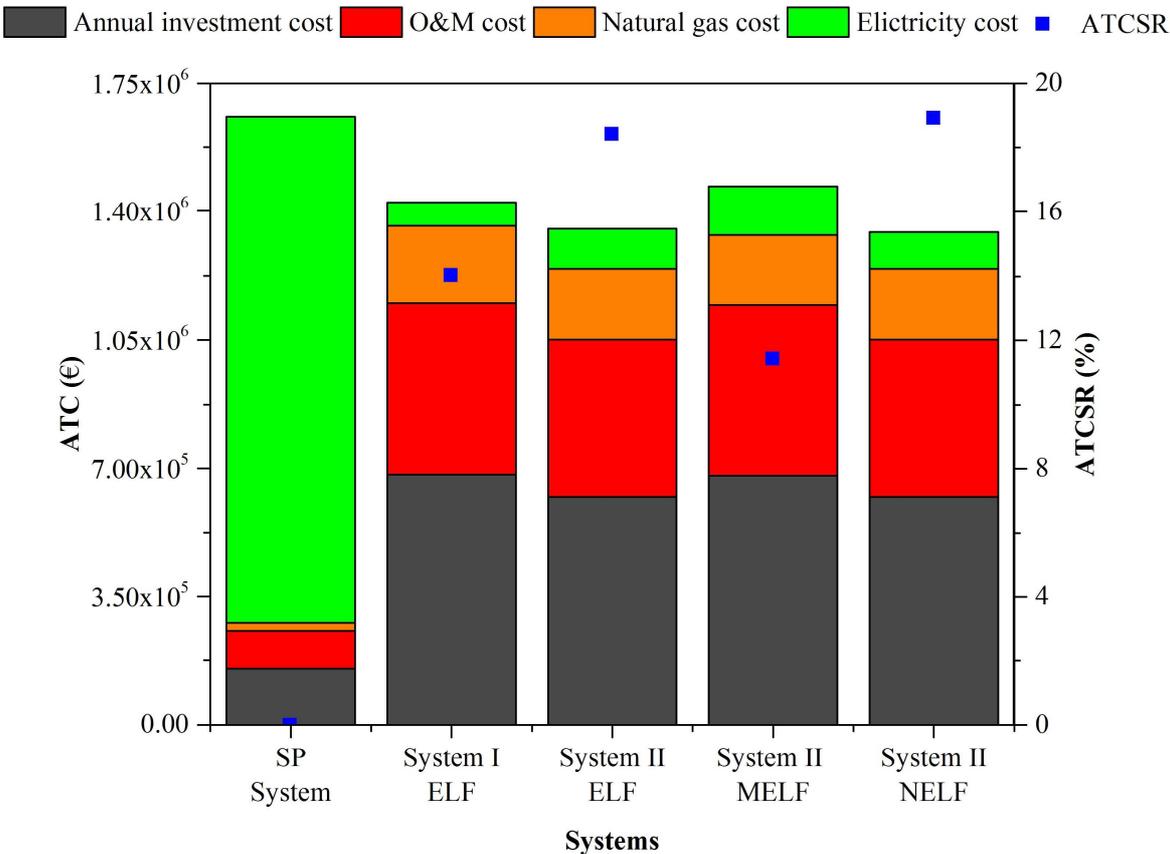


Fig. 12. Annual ATC and ATCSR of the reference and CCHP systems.

Fig. 13 shows the CDE and CDERR of the optimized CCHP systems. Generally speaking, in the Mosque complex, the introduction of the CCHP system leads to better environmental performance than the energy and economic performance discussed above. As can be seen, all of the CCHP systems can significantly reduce CDE and achieve satisfying CDERR. For all the CCHP systems, the majority of carbon dioxide emissions come from PGU, due to its high consumption of natural gas to meet the electricity demand. On the other hand, the design of CCHP system with hybrid chiller results in larger CDERR than absorption chiller only based CCHP system. This is due to the high boiler gas consumption in system I to meet the heat demand for cold production in absorption chiller only based CCHP system and to the high COP of the electric chiller which reduce the energy consumption for cold production in the hybrid chiller based CCHP systems. As a result, the order of magnitude of the CDERRs for each system is the same as that of the PESRs. This is attributable to the fact that all energy requirements fulfilled by the CCHP systems are essentially generated by the consumption of natural gas. The more primary energy consumption is required, the more carbon dioxide is emitted. Thus, the hybrid chiller CCHP system based NELF strategy enjoys the best environmental performance with a CDERR close to 24%, followed by the MELF strategy and ELF strategy. Therefore, the hybrid chiller CCHP system is considered to be the most suitable choice for the Mosque complex. Otherwise, due to the size of the prime mover, the hybrid chiller CCHP system based NELF strategy is the best option with the highest CDERR compared to the other design and management modes.

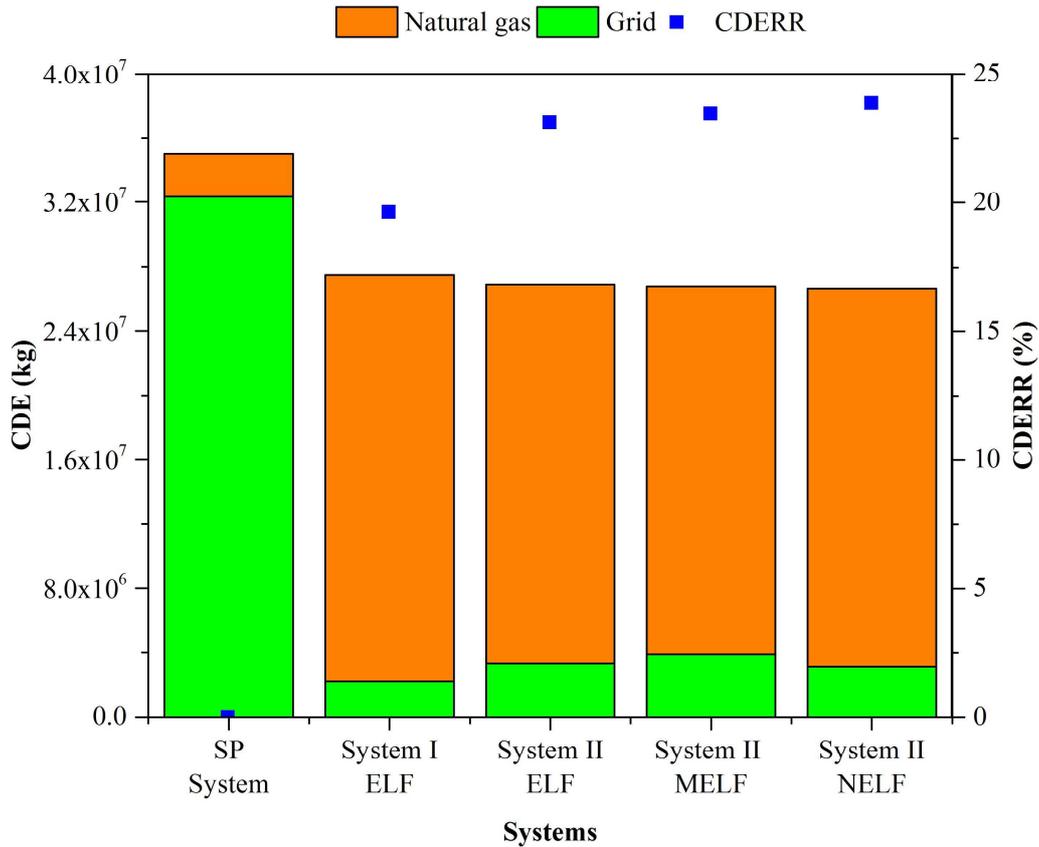


Fig. 13. Annual CDE and CDERR of the reference and CCHP systems.

Figs. 14–16 show the monthly PESR, CDERR, and ATCSR compared with the SP system for the different systems. It can be seen that all variations in all CCHP systems are positive. Furthermore, irrespective of the design or strategy employed, the performance of the CCHP system are superior to that of the separate system. While, the variation of CDERR is the largest, followed by the variation of PESR and the smallest variation is related to ATCSR. Figures also reveal that for all CCHP designs and strategies in the cold winter and hot summers such as January, August, and December the values of CDERR and PESR are low, while in the transition seasons such as May, June, and October, the values are high. Conversely, the trend of the ATCSR is opposite to that of the PESR and CDERR, in hot summer and transition season, the values of ATCSR are large, while in winter the values are small.

The main reason is in the transition season, the thermal load is lower and the heat/electric ratio is therefore lower. In this situation, the heat to power demand rate becomes closer to the rate of heat to power generated by PGU, which results in a better use of the PGU

recovered heat and thus an increase in the energetic and environmental performances. In hot summer, the heating and cooling demand are higher, and the recovered heat is often unable to meet the required thermal demand. The remaining heat is supplied by the boiler and the remaining cold is supplied by the electrical chiller. The increased natural gas and electrical demand are imported from the grid. Therefore, the energetic and environmental performance are less than that in the transition season. In the cold winter, the heat/electricity ratio is low and the heat recovered from the PGU can meet the whole thermal requirement. In this situation, the excess heat is rejected in the environment, which decreases the energetic and environmental performance in the winter compared to the transition season.

Compared to the other seasons, absorption chiller only CCHP system in summer has no significant advantage over SP systems, since absorption chiller has a relatively low COP, which decreases the energy consumption performance of the system and affects the economical and the environmental performance.

For the hybrid chiller CCHP system, which also meets some of the cooling needs in summer by the combination of the absorption chiller and the gas boiler, the use of the gas boiler is much less than that of an absorption chiller only CCHP system. However, the electric chiller meets the largest part of the cooling demand with a high COP compared to the COP of an absorption chiller. Therefore, System II still has good performance in summer.

For the monthly ATCSR, CCHP systems may reduce monthly costs for all the examined CCHP systems compared to the SP system, especially in summer (Fig. 15), despite the energy consumption increase in this season (see Fig. 17). This is mainly due to the reduction of the electricity consumption in CCHP systems compared to SP system and to the high electricity/natural gas price ratio (Fig. 18 and Tab. 3).

The monthly energy costs dramatically increase during the summer caused by the high energy demand during the summer months compared to other months, and the increase of the electricity consumption. However, in winter and transition seasons, the variations of the monthly electricity costs are relatively small due to the small energy demand variation compared to energy demand variation in summer season.

Our results highlight that the economic performances of CCHP systems are extremely sensitive to electricity and natural gas tariffs. However, according to current economic parameters, the economic performances of the hybrid chiller CCHP system under NELF and ELF strategies are quite close, and they are the most recommended systems for the Mosque among all the systems proposed from an economic point of view.

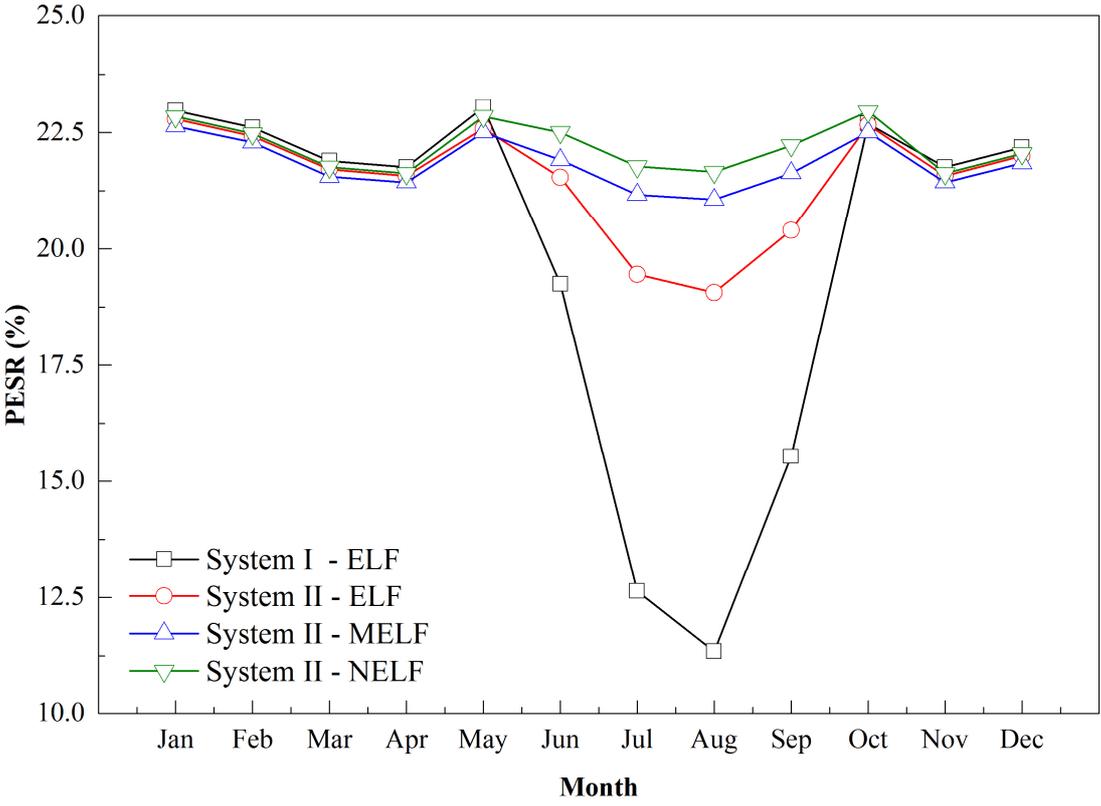


Fig. 14. Monthly PESR of the CCHP systems.

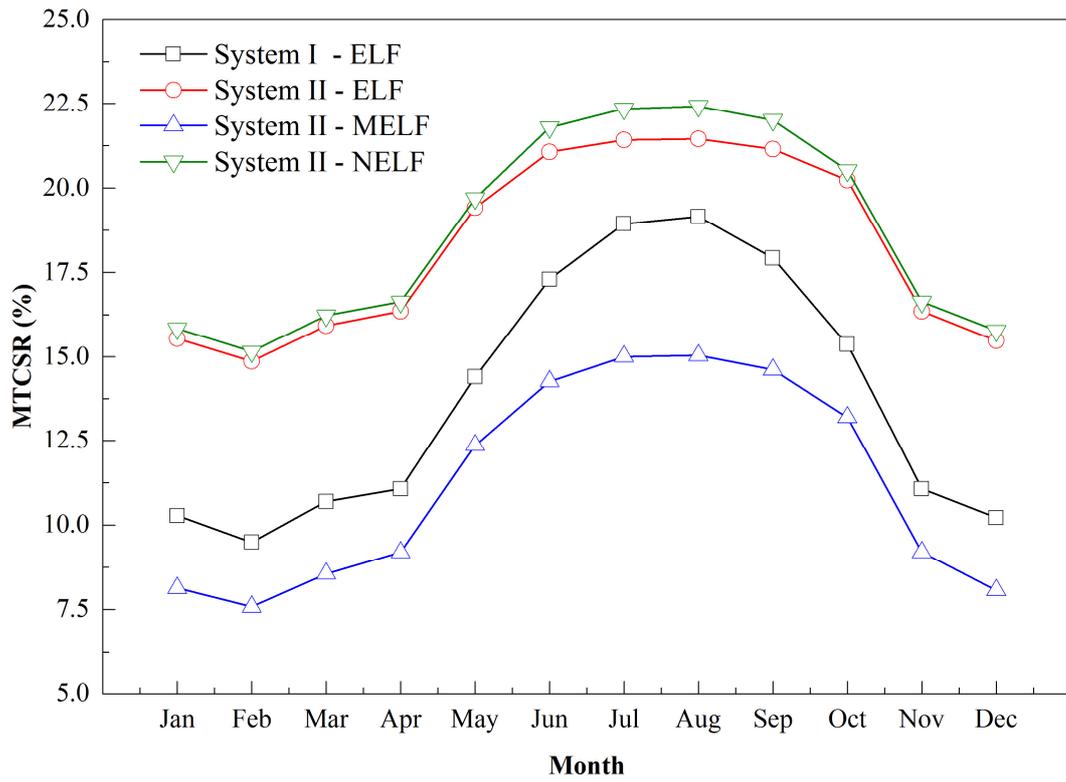


Fig. 15. Monthly TCSR of the CCHP systems.

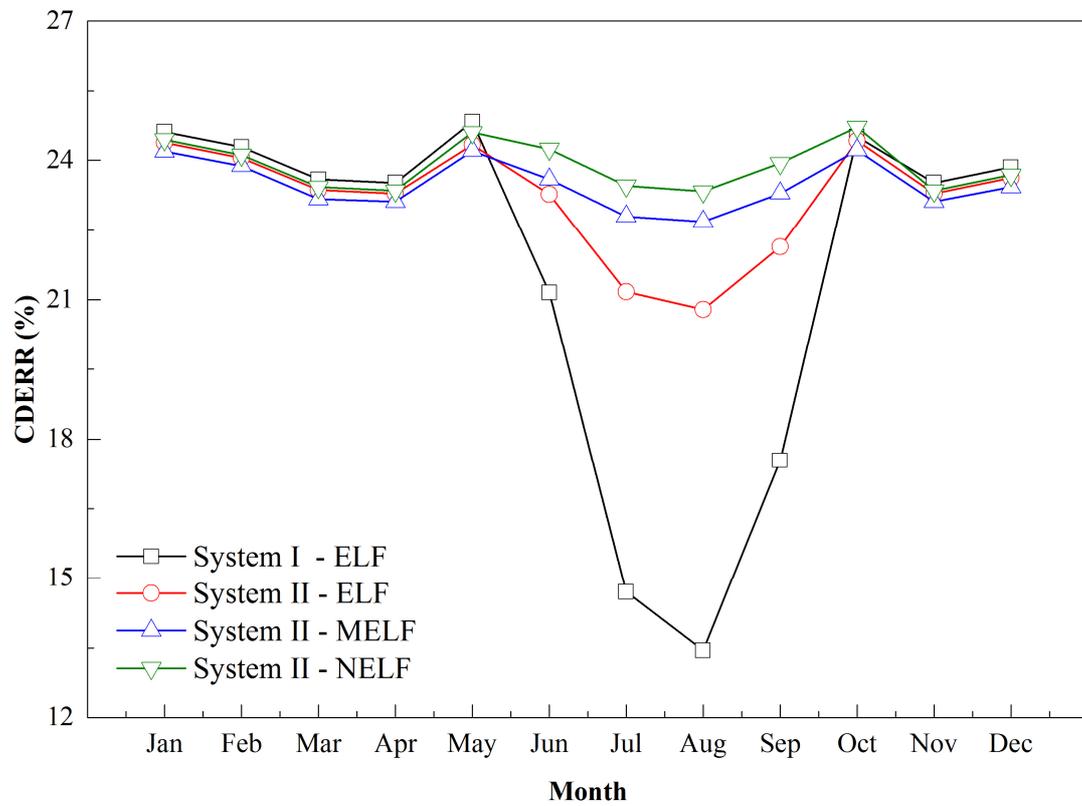


Fig. 16. Monthly CDERR of the CCHP systems.

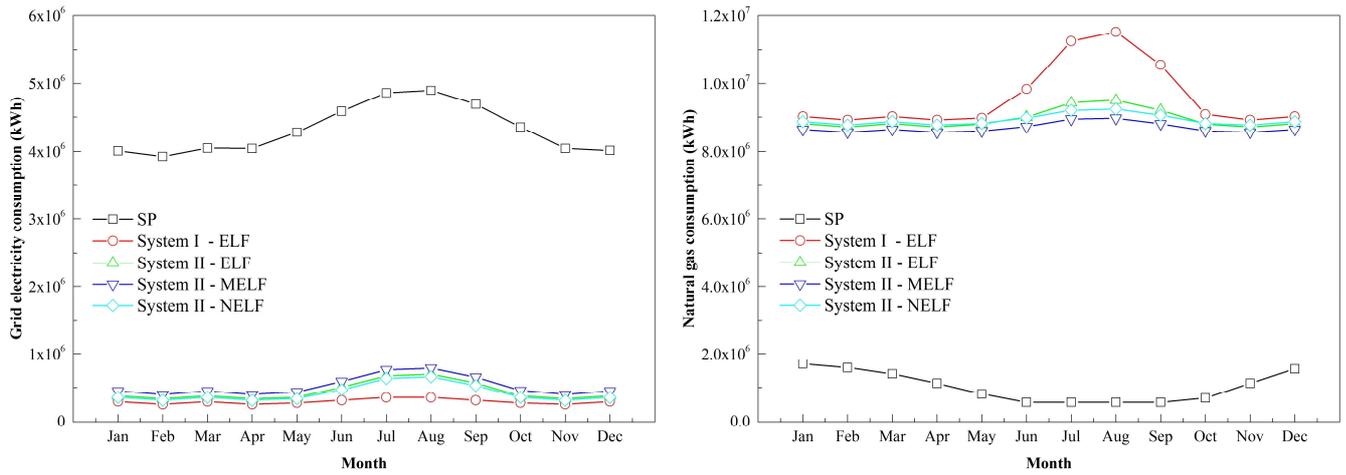


Fig. 17. Monthly grid electricity and natural gas consumption.

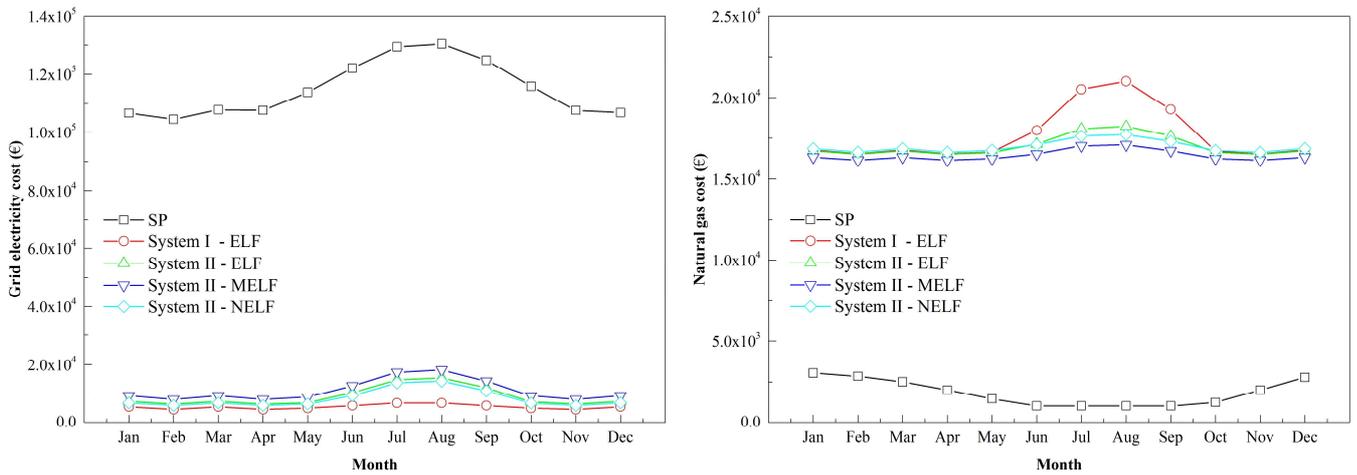


Fig. 18. Monthly grid electricity and natural gas cost.

6. Conclusion

In this paper, a new electric load following (NELF) strategy for CCHP system with hybrid chiller was proposed to supply the cooling, heating and electricity demands of a Mosque complex located in Algiers, Algeria. The NELF for CCHP system with hybrid chiller was analyzed and compared with separated production system (SP), CCHP system with absorption chiller only under ELF strategy and with hybrid chiller under ELF and MELF strategies. The systems configurations were optimized by using multi-objective optimization method, based on primary energy consumption, annual total cost and carbon dioxide emission criteria, and by using decision-making approach. As the results show, the CCHP system with hybrid chiller under NELF, in addition to its economic feasibility, has a significant

capacity to reduce fuel consumption and pollutant emissions. The main study results can be summed up as follows:

- From an energetic, economic and environmental point of view, the introduction of CCHP systems is a viable option to be applied in the Mosque complex with high benefits due to the higher electricity price and the lower price of natural gas.
- During the summer months, the performance of the absorption chiller only CCHP system under ELF strategy decreases due to the high heat to power ratio and the relatively low COP of the absorption chiller.
- The hybrid chiller CCHP System is the most suitable configuration for the mosque application. Where the performance of all the operational strategies for this configuration show a similar trend.
- The MELF strategy for the CCHP system with a hybrid chiller is not a recommended strategy due to its high initial investment cost which leads to low economic benefits.
- Considering the overall performance, the NELF strategy provided more benefits in comparison with other strategies in all studied criteria. The NELF strategy showed 22.19%, 19.03% and 23.88% improvement in PESR, ATCSR and CDERR respectively, in comparison to the conventional system.

Future works could be directed towards exploring and comparing the performance of the new strategy with other CCHP systems using different prime mover technologies and integrating other energy sources such as bioenergy and solar energy. This would allow interested researchers to efficiently select the right design parameters and strategies for their CCHP systems.

Reference

- [1] Nehring R. Traversing the mountaintop: world fossil fuel production to 2050. *Philos Trans R Soc B Biol Sci* 2009;364:3067–79. doi:<https://doi.org/10.1098/rstb.2009.0170>.
- [2] IEA (2017), *World Energy Outlook 2017*, IEA, Paris
<https://www.iea.org/reports/world-energy-outlook-2017>.
- [3] Ahmadi MH, Alhuyi Nazari M, Sadeghzadeh M, Pourfayaz F, Ghazvini M, Ming T, et al. Thermodynamic and economic analysis of performance evaluation of all the thermal power plants: A review. *Energy Sci Eng* 2019;7:30–65.
- [4] Fumo N, Mago PJ, Chamra LM. Analysis of cooling, heating, and power systems based on site energy consumption. *Appl Energy* 2009;86:928–32.
- [5] Ghaebi H, Yari M, Gargari SG, Rostamzadeh H. Thermodynamic modeling and optimization of a combined biogas steam reforming system and organic Rankine cycle for coproduction of power and hydrogen. *Renew Energy* 2019;130:87–102.
- [6] Wang J-J, Jing Y-Y, Zhang C-F. Optimization of capacity and operation for CCHP system by genetic algorithm. *Appl Energy* 2010;87:1325–35.
- [7] Kerr T. Combined heat and power: evaluating the benefits of greater global investment. IEA, Int Energy Agency Website-Retrived from <Http://Www Eia Gov/On> 2008;1:2015.
- [8] Al Moussawi H, Fardoun F, Louahlia H. Selection based on differences between cogeneration and trigeneration in various prime mover technologies. *Renew Sustain Energy Rev* 2017;74:491–511.
- [9] Zhang J, Cao S, Yu L, Zhou Y. Comparison of combined cooling, heating and power (CCHP) systems with different cooling modes based on energetic, environmental and economic criteria. *Energy Convers Manag* 2018;160:60–73.
- [10] Cho H, Mago PJ, Luck R, Chamra LM. Evaluation of CCHP systems performance based on operational cost, primary energy consumption, and carbon dioxide emission by utilizing an optimal operation scheme. *Appl Energy* 2009;86:2540–9.

- [11] Wang J-J, Jing Y-Y, Zhang C-F, Zhai ZJ. Performance comparison of combined cooling heating and power system in different operation modes. *Appl Energy* 2011;88:4621–31.
- [12] Mago PJ, Hueffed AK. Evaluation of a turbine driven CCHP system for large office buildings under different operating strategies. *Energy Build* 2010;42:1628–36.
- [13] Smith A, Luck R, Mago PJ. Analysis of a combined cooling, heating, and power system model under different operating strategies with input and model data uncertainty. *Energy Build* 2010;42:2231–40.
- [14] Jing Y-Y, Bai H, Wang J-J, Liu L. Life cycle assessment of a solar combined cooling heating and power system in different operation strategies. *Appl Energy* 2012;92:843–53.
- [15] Afzali SF, Mahalec V. Optimal design, operation and analytical criteria for determining optimal operating modes of a CCHP with fired HRSG, boiler, electric chiller and absorption chiller. *Energy* 2017;139:1052–65.
- [16] Wang J, Yang Y, Mao T, Sui J, Jin H. Life cycle assessment (LCA) optimization of solar-assisted hybrid CCHP system. *Appl Energy* 2015;146:38–52.
- [17] Wang J, Zhai ZJ, Jing Y, Zhang C. Particle swarm optimization for redundant building cooling heating and power system. *Appl Energy* 2010;87:3668–79.
- [18] Hajabdollahi H, Ganjehkaviri A, Jaafar MNM. Assessment of new operational strategy in optimization of CCHP plant for different climates using evolutionary algorithms. *Appl Therm Eng* 2015;75:468–80.
- [19] Li M, Mu H, Li N. Optimal design and operation strategy for integrated evaluation of CCHP (combined cooling heating and power) system. *Energy* 2016;99:202–20.
- [20] Li Y, Hu R. Exergy-analysis based comparative study of absorption refrigeration and electric compression refrigeration in CCHP systems. *Appl Therm Eng* 2016;93:1228–37.
- [21] Ahn H, Rim D, Freihaut JD. Performance assessment of hybrid chiller systems for

- combined cooling, heating and power production. *Appl Energy* 2018;225:501–12.
- [22] Lai SM, Hui CW. Feasibility and flexibility for a trigeneration system. *Energy* 2009;34:1693–704.
- [23] Ziher D, Poredos A. Economics of a trigeneration system in a hospital. *Appl Therm Eng* 2006;26:680–7.
- [24] Pagliarini G, Corradi C, Rainieri S. Hospital CHCP system optimization assisted by TRNSYS building energy simulation tool. *Appl Therm Eng* 2012;44:150–8.
- [25] Gu Q, Ren H, Gao W, Ren J. Integrated assessment of combined cooling heating and power systems under different design and management options for residential buildings in Shanghai. *Energy Build* 2012;51:143–52.
- [26] Chua KJ, Yang WM, Er SS, Ho CA. Sustainable energy systems for a remote island community. *Appl Energy* 2014;113:1752–63.
- [27] Abbasi M, Chahartaghi M, Hashemian SM. Energy, exergy, and economic evaluations of a CCHP system by using the internal combustion engines and gas turbine as prime movers. *Energy Convers Manag* 2018;173:359–74.
- [28] Ahn H, Freihaut JD, Rim D. Economic feasibility of combined cooling, heating, and power (CCHP) systems considering electricity standby tariffs. *Energy* 2019;169:420–32.
- [29] Gao L, Hwang Y, Cao T. An overview of optimization technologies applied in combined cooling, heating and power systems. *Renew Sustain Energy Rev* 2019;114:109344.
- [30] Mohammadkhani N, Sedighizadeh M, Esmaili M. Energy and emission management of CCHPs with electric and thermal energy storage and electric vehicle. *Therm Sci Eng Prog* 2018;8:494–508.
- [31] Khaloie H, Abdollahi A, Shafie-Khah M, Siano P, Nojavan S, Anvari-Moghaddam A, et al. Co-optimized bidding strategy of an integrated wind-thermal-photovoltaic system in deregulated electricity market under uncertainties. *J Clean Prod* 2020;242:118434.
- [32] Khaloie H, Abdollahi A, Shafie-Khah M, Anvari-Moghaddam A, Nojavan S, Siano P, et

- al. Coordinated wind-thermal-energy storage offering strategy in energy and spinning reserve markets using a multi-stage model. *Appl Energy* 2020;259:114168.
- [33] Jing R, Wang M, Wang W, Brandon N, Li N, Chen J, et al. Economic and environmental multi-optimal design and dispatch of solid oxide fuel cell based CCHP system. *Energy Convers Manag* 2017;154:365–79.
- [34] Cao Y, Wang Q, Du J, Nojavan S, Jermittiparsert K, Ghadimi N. Optimal operation of CCHP and renewable generation-based energy hub considering environmental perspective: An epsilon constraint and fuzzy methods. *Sustain Energy, Grids Networks* 2019;20:100274.
- [35] Hou J, Wang J, Zhou Y, Lu X. Distributed energy systems: Multi-objective optimization and evaluation under different operational strategies. *J Clean Prod* 2020:124050.
- [36] Abbasi MH, Sayyaadi H, Tahmasbzadebaie M. A methodology to obtain the foremost type and optimal size of the prime mover of a CCHP system for a large-scale residential application. *Appl Therm Eng* 2018;135:389–405.
- [37] Yan Y, Zhang C, Li K, Wang Z. An integrated design for hybrid combined cooling, heating and power system with compressed air energy storage. *Appl Energy* 2018;210:1151–66.
- [38] Chen X, Zhou H, Li W, Yu Z, Gong G, Yan Y, et al. Multi-criteria assessment and optimization study on 5 kW PEMFC based residential CCHP system. *Energy Convers Manag* 2018;160:384–95.
- [39] Song Z, Liu T, Lin Q. Multi-objective optimization of a solar hybrid CCHP system based on different operation modes. *Energy* 2020;206:118125.
- [40] Deb K, Pratap A, Agarwal S, Meyarivan T. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans Evol Comput* 2002;6:182–97.
- [41] National Agency of Realization and Management of Djamaa El Djazair (ANARGEMA). No Title n.d.
- [42] Lai SM, Hui CW. Integration of trigeneration system and thermal storage under

- demand uncertainties. *Appl Energy* 2010;87:2868–80.
- [43] Konak A, Coit DW, Smith AE. Multi-objective optimization using genetic algorithms: A tutorial. *Reliab Eng Syst Saf* 2006;91:992–1007.
- [44] Holland JH. *Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence*. MIT press; 1992.
- [45] Ren F, Wang J, Zhu S, Chen Y. Multi-objective optimization of combined cooling, heating and power system integrated with solar and geothermal energies. *Energy Convers Manag* 2019;197:111866.
- [46] World energy council n.d. <https://wec-indicators.enerdata.net/secteur.php#/power-generation-efficiency.html>.
- [47] World bank n.d. <https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=DZ>.
- [48] Guezgouz M, Jurasz J, Bekkouche B. Techno-economic and environmental analysis of a hybrid PV-WT-PSH/BB standalone system supplying various loads. *Energies* 2019;12:514.
- [49] Fang F, Wei L, Liu J, Zhang J, Hou G. Complementary configuration and operation of a CCHP-ORC system. *Energy* 2012;46:211–20.
- [50] Zhang X, Zeng R, Mu K, Liu X, Sun X, Li H. Exergetic and exergoeconomic evaluation of co-firing biomass gas with natural gas in CCHP system integrated with ground source heat pump. *Energy Convers Manag* 2019;180:622–40.
- [51] Ahmadi MH, Sayyaadi H, Dehghani S, Hosseinzade H. Designing a solar powered Stirling heat engine based on multiple criteria: maximized thermal efficiency and power. *Energy Convers Manag* 2013;75:282–91.
- [52] Kahraman C. *Fuzzy multi-criteria decision making: theory and applications with recent developments*. vol. 16. Springer Science & Business Media; 2008.
- [53] Xia H-C, Li D-F, Zhou J-Y, Wang J-M. Fuzzy LINMAP method for multiattribute decision making under fuzzy environments. *J Comput Syst Sci* 2006;72:741–59.

- [54] Krohling RA, Campanharo VC. Fuzzy TOPSIS for group decision making: A case study for accidents with oil spill in the sea. *Expert Syst Appl* 2011;38:4190–7.
- [55] Sayyaadi H, Mehrabipour R. Efficiency enhancement of a gas turbine cycle using an optimized tubular recuperative heat exchanger. *Energy* 2012;38:362–75.