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A novel methodology to compare between optimized CCHP and optimized Solar-CCHP system

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Abstract— Solar collectors (SCs) and Photovoltaics (PVs) can intervene with trigeneration systems to form a polygeneration system. Many studies have accessed this intervention, however, these studies depended on the performance of these components as individual components not on a system basis. They haven't dealt with the environmental and exergetic aspects of the whole system. Moreover, they haven't dealt with optimal planning and scheduling of these systems. A methodology of real system-level comparison is presented in contrary to component-level comparisons that are available in the open literature. This methodology depends on comparing an optimized Solar-CCHP polygeneration system with side-by-side PVs and SCs, against an optimized CCHP (Combined heating, cooling and power) system. The comparison is under the constraints of maximizing a formulated combined efficiency that combines energy, economy, environment and exergy aspects. Results showed that the Solar-CCHP system has higher combined efficiency but with lower Net Present Value (NPV). Another novel contribution for determining the actual selling price of both sold CCHP-electricity and Solar-electricity is presented. These results assured the importance of reducing the capital costs of solar energy systems to facilitate its deployment in future energy systems as they already prove their ability to increase overall combined efficiency of energy systems by decreasing the fuel used and emission produced.

Keywords—Trigeneration, Photovoltaics, Solar Thermal collectors, CCHP, Solar-CCHP, Comparison, Optimization

I. INTRODUCTION

According to recent BP statistics [1], growth of global primary energy consumption has increased to 2.2%, which is considered the fastest growth since 2013. In Egypt, With the unlikelihood of a massive deployment of renewable energy in Egypt, the preceding numbers are expected to grow, seeing the dependence on large thermal power plants with deteriorated efficiency and high investment, operational and transmission costs. As such, the cost of electricity purchase and carbon emissions are expected to rise.

Combined cooling, heating and power (CCHP) microgrid is a type of trigeneration that allows use of fuel and renewable energy resources with efficient, economic and environmentally friendly operation. Trigeneration can increase also the energy utilization efficiency up to 80% [3]. However, the problem of optimal planning, sizing and scheduling of trigeneration systems has been the main concern of energy specialists for a long time due to the complexity of achieving all the goals of sustainable development (saving energy, reduce emissions, increase efficiency and cut down costs) [4].

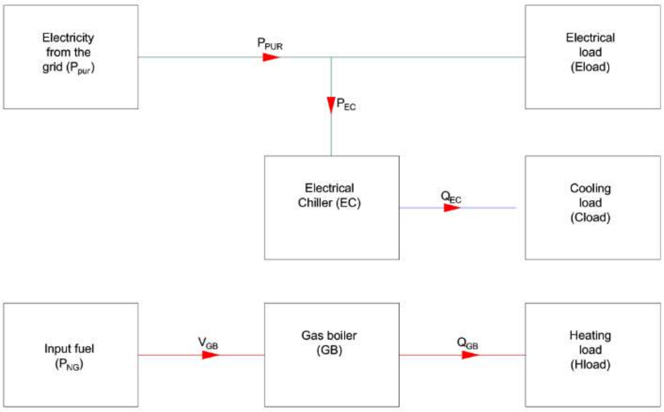

Fig. 1 Reference system

Active solar utilization is from the key parameters for solving energy problems to save resources and environment in Egypt. Despite its advantages, solar energy remains a small fraction of the world's total energy supply (below 2%) [1]. On a global scale, Egypt is one of the most appropriate regions for exploiting solar energy both for electricity generation and thermal heating applications [2].

In addition to the importance of using solar energy, the maturity of the trigeneration technologies offered a great potential to use them together. Accordingly, the deployment of both together became the interest of many research papers. These papers studied the effect of using solar energy components in a trigeneration system. Nosrat et al. [3] optimized the design of a PV-CHP system to reduce cost and emissions using Photovoltaic-Trigeneration Optimization Model (PVTOM). Brandoni and Renzi [4] pointed out to the importance of sizing hybrid renewable energy systems, in particular the micro-CHP unit, in order to maximize the economic and the energy savings with respect to conventional generation. They also analyzed the advantages and limitations of introducing a high concentration solar energy system (HCPV) compared to silicon PV systems was presented. Results showed that the internal combustion engine (ICE) performed better than other prime movers due to higher electrical efficiency and lower investment cost. Moreover, a 16.7% energy saving compared to conventional generation can be achieved.

HCPV provided a higher reduction in CO2 emissions than PV one, better results in terms of minimization of the total annualized cost were shown by PV, due to its lower investment cost that actually threatens the market penetration of the HCPV technology. Ramos et al. [5] considered the techno-economic challenges of PV/T systems aiming at a low cost per kWh of trigeneration. Results showed an overall levelized cost to be in the range of 0.06–0.12 €/kW h, which is 30–40% lower than that of equivalent PV-only systems. Su et al. [6] proposed a novel CCHP system by combining concentrated photovoltaic/thermal (PV/T) technology with an advanced air-handling process that realizes independent control of temperature and humidity. Due to the efficient use of solar energy, annual energy saving ratio and CO2 emissions reduction ratio are predicted to be 73.28% and 74.55%, respectively. The integrated performance, considering energy, environment and economic factors, reaches 37.48% when no excess heat from PV/T collector is used, and it can be further improved by thermal storage or recovering the excess heat to produce other products.

Kasaeian et al. [7] conducted a critical review of the literature on solar combined heat and power systems (CHP), which includes solar photovoltaic/thermal systems, concentrated photovoltaic/thermal systems, and various combination with different solar collectors and applications. It showed that there are serious gaps in this field, which calls for more research. There are limited studies on the economic and exergy assessments of the solar concentrating CHP systems. The solar collectors for combined CHP were focused on optimizing the performance of the maximum average useful power generation and minimum total heat transfer area, little environment impact analysis was conducted. They suggested careful exergy, economic and environmental analysis on both electronic and thermal performance, especially for large CHP system. Also, they recommended further studies for investigating the hybrids of concentrating collectors with CHP, with considering the economic issues.

At the end of the day, an efficient component in a nonefficient system isn't the objective but the main objective is an efficient system that contains efficient components working simultaneously. Using this concept comparison of Solar-CCHP polygeneration system (a trigeneration system with side-by-side photovoltaics and thermal collectors) to a CCHP trigeneration system under fixed available roof area is more realistic than comparing only the energies produced or the area used by side-by-side PVs and SCs.

This methodology guarantees more improvement in system performance after allowing the configuration, sizing and scheduling of the original CCHP system to change after the solar intervention.

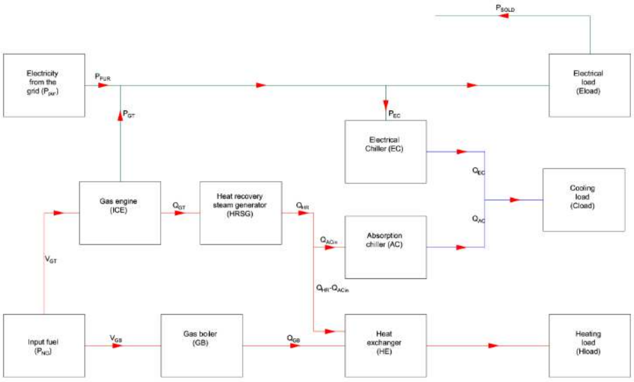

Fig. 2 CCHP System

II. METHODOLOGY

A. *Systems description and novel contributions*

This paper studies one conventional system, an optimized trigeneration system and a Solar-CCHP polygeneration system as shown in Fig.1-3. The conventional system which is taken as a reference system consists of an electric chiller (EC), a gas boiler (GB) and grid electricity. The CCHP consists of ICE, GB, absorption chiller (AC), EC, heat exchanger (HE) and heat recovery steam generator (HRSG). A Solar-CCHP system that comprises of PVs and SCs side-by-side along with CCHP. Both systems are grid-connected. The energy flows are shown in these figures, lines with different colors stand for different energy carriers: green ones indicate electricity, red ones and blue ones for heating and cooling energy provided for users respectively.

The scenario for satisfying the electrical load is the same for both systems, where the PV has the priority to provide electrical output at first then the ICE and purchased electricity from the grid provide the rest. This is done to maximize solar energy utilization. While if ICE produces electricity more than the user needs, the excess electricity will be sold back to the grid. The grid is using natural gas as fuel in this paper. Whereas the heating load is satisfied by the heat produced by the collectors as a priority and then the heat recovered from the ICE and that produced by boiler supply the rest. The system is constrained not to produce excess heat than what is required by the heating load or the AC. The cooling is provided by the AC and EC.

This paper also provides a methodology to compare such systems based on the energy hub concept under the constraints of maximizing a formulated combined efficiency that contains annualized total cost saving ratio (ATCSR), exergy efficiency (EXEff), fuel saving ratio (FSR) and carbon dioxide reduction ratio (CO2RR) using a weighing factor method. This is made by comparing each indicator to a conventional system in GAMS using the RMINLP solver. Two-level binary variables are used to determine optimal system configuration and optimal hourly scheduling.

Using part load effect and variable capital costs of components to simulate the real case, the tool provides optimal planning, sizing and scheduling of all polygeneration systems.

Another important contribution of this paper, is that it defines a criterion for determining the minimum selling prices of electricity produced from the CCHP and solar devices by determining the cost of electricity production. It also proposes a profit margin for the investors.

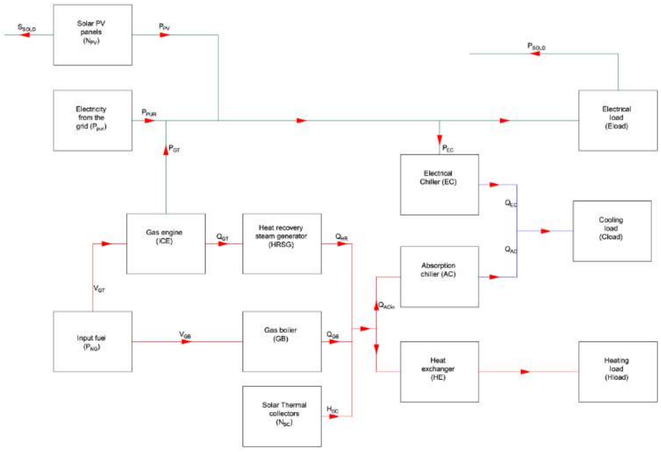

Fig. 3 Solar-CCHP system

B. *Assumptions used in the model*

- The study period is taken to be a whole year but 12 time steps that represent each month are studied to facilitate the study [8].
- The system is grid connected, selling and purchasing are allowable.
- The part load performance of all components is studied with 30% minimum part load to guarantee good performance as most of mechanical components' performance deteriorate below 30% [9]
- Hybrid load following (FHL) operating strategy, in which smaller load between electrical or cooling and heating is satisfied first, is followed [10].
- The project's lifetime is assumed to be 20 years with an interest rate of 17.25% [11].
- The modeling equations have been taken from previously published papers [8,12–17].

C. *Electricity selling price*

A novel contribution is presented to formulate a formula to calculate the cost of producing electricity from the trigeneration system considering electricity as the main output. It calculates the share of investment, maintenance and operation cost at the same time t of generation to produce more accurate results. This actual selling price is as follows:

$$ESP(t) = k.\left(ecost(t) + e(t)\right) \quad (1)$$

$$ecost(t) = \frac{\frac{CRF_{ICE}.CAP_{ICE}.P_{ICEN}}{8760} + M_{ICE}.P_{ICE}(t) + g(t).V_{ICE}(t)}{P_{ICE}(t)} \quad (2)$$

where ecost(t), e(t) and g(t) are the cost of producing 1 kWh of electricity from the CCHP system at time t and the cost of electricity and gas purchase from the utility at time t respectively. CRF_{ICE}, C_{ICE}, P_{ICEN} and M_{ICE} are capital recovery factor, capital cost, rated capacity and maintenance cost of ICE. P_{ICE} (t) and V_{ICE}(t) are the power produced and gas consumed by the ICE at time t respectively. The same criterion was used to determine the actual cost of solar generation at time t.

$$SSP(t) = k.(scost(t) + e(t)) \quad (3)$$

$$scost(t) = \frac{A_{PV}.N_{PV}.CAP_{PV}.CRF_{PV}}{8760P_{PV}(t)} \quad (4)$$

where scost(t) is the cost of producing 1 kWh of electricity from the Solar system at time t. A_{PV}, N_{PV}, CAP_{PV} and CRF_{PV} are area, number, capital cost and capital recovery factor of PV panel respectively while the P_{PV}(t) is the power produced by PV panel. The k-factor is introduced to give the flexibility to for the decision-maker to take a percentage of the minimum selling price calculated depending on the constraints facing selling electricity to the main grid.

D. *Objective function formulation*

The formulated objective function contains the weighted KPIs (ATC, EXEff, CO2RR and FSR) as follows:

$$Combined\ efficiency = w_1.ATCSR + w_2.FSR + w_3.CO2RR + w_4.EXEff \quad (5)$$

$$Objective\ function = \frac{1}{Combined\ efficiency} \quad (6)$$

As an example of user input of weighing factors (w), a weighting factor of 0.25 is given to each KPI. According to [18] equal weights produce more optimal results so equal weights are assumed in our study.

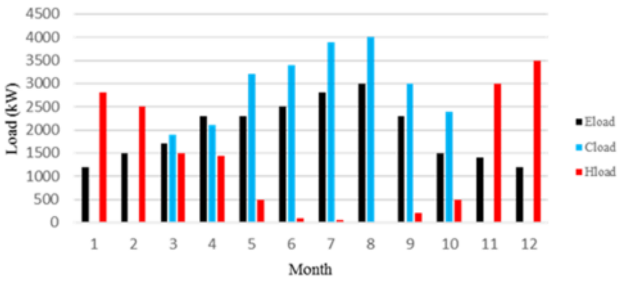

Fig. 4 Monthly demand data

III. CASE STUDY DESCRIPTION

To study the performance of the trigeneration system, a case study of a typical residential compound in Egypt of roof area percentage of 20% from the whole building area is adopted that has load demand as shown in Fig. 4. with peak loads of electricity, heating and cooling are 3000 kW_e, 3500 kW_t and 4000 kW_c respectively. Capital costs of prime movers and chillers vary with their rated capacities of components [17,19,20].There are different values emission factors for grid and prime mover [21].

A. *Input data*

The data in this paper have been obtained from previous published papers, CHP guide and manufacturers catalogues [8,12,14,15,17,21–25].

B. *ToU pricing method*

An assumed tariff using a ToU pricing method was used for buying electricity, where electricity price is at its maximum value at peak demand periods and decreases in off seasons which will render the trigeneration option more desirable as shown in Fig. 5. Natural gas price is assumed constant, as no variation occurs throughout the year in

Egypt[26].

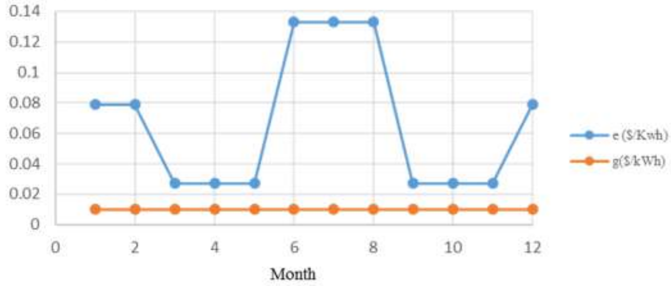

Fig. 5 Variation of electricity and gas prices

TABLE I RESULTS OF THE TWO SYSTEMS

Parameter	CCHP system	Solar-CCHP System
ATCSR	11.9%	9.2%
FSR	33.3%	35.2%
CO2RR	29.6%	31.9%
Exergy efficiency	41.2%	41.1%
Combined efficiency (%)	28.99%	29.34%
Capacity of ICE (kW)	2034	1791
Capacity of HRSG (kW)	1945	1746
Capacity of AC (kW)	4000	4000
Capacity of EC (kW)	0	0
Capacity of Boiler (kW)	1554	1694
Capacity of HE (kW)	3500	3500
Number of PV (N_{PV})	-	449
Number of SC (N_{SC})	-	636
Thermal energy provided by solar devices (kWh)	-	2,166,786
Electrical energy provided by solar devices (kWh)	-	216,883
Thermal Solar fraction (TSF)	-	9.76%
Electrical Solar fraction (ESF)	-	1.04%
Purchased gas (kWh)	47,616,000	43,048,000
Purchased electricity (kWh)	3,641,300	4,502,300
Annual revenues from selling electricity ($)	10779.2	5924.1
ATC ($)	1,830,300	1,887,600
Net annual cash flow (NCF) ($) considering savings of using trigeneration	247,790	190,530
Payback Period (PBP) (Years)	9.937	15.087
Internal rate of return (IRR) (per year)	7.84%	2.85%
Cost of selling CCHP electricity from the system ($/kWh)	0.062	0.062
Cost of selling Solar electricity from the system ($/kWh)	-	Ranges from 0.134 in summer to 0.324 in winter

IV. RESULTS AND DISCUSSION

A. *Planning*

Although that each system had its unique components, both of them didn't contain an electric chiller because it consumes expensive electricity generated from the ICE or bought from the grid while absorption chiller consumes cheap recovered heat or heat coming from the boiler. This leads to the conclusion that the capacity of the optimized absorption chiller is equal to the peak cooling load (4000 kW_c). Accordingly, there is no much effect of adding solar energy into components selection.

B. *Sizing*

As the solar collectors and the PVs contribute to supplying the needed load, the capacity of the ICE and the HRSG decreased as shown in Table 1-2, while a slight increase was noticed in boiler's capacity. This increase in the boiler capacity was to supply the heating load at the peak months such as Dec where the solar contribution is smaller as well as that of the ICE as shown in Fig.10.

C. *Scheduling*

At the beginning, the scheduling of cooling load as shown in Fig. 6 is the same in both models as the absorption chiller is the only component that provides cooling.

However, for the electrical load, it is clear in Fig. 7-8 that in the in CCHP system, the ICE supplied minimum of 56.6% of the load throughout the year. and purchased grid electricity took place in months from Apr to Oct while sold CCHP-electricity took place in rest of the year. On the contrary in the Solar-CCHP system, the ICE supplied minimum of 49.6% of the load throughout the year and purchased grid electricity took place in months from Mar to Oct while sold CCHP-electricity and solar electricity took place in rest of the year.

The contribution of the PV is clear in summer more than in winter achieving an electrical solar fraction (ESF) of 1.09% due to the effect of solar radiation. Moreover, all solar electricity produced in winter was sold to the grid.

The share of the gas boiler in supplying the heating load increased in the Solar-CCHP system in winter months while it decreased in summer months. This is because the introduction of heat produced by solar collectors is significant in summer more in winter as shown in Fig. 9-10. A thermal solar fraction (TSF) of 9.76% is achieved by the solar collectors. While the share of the ICE and HRSG decreased throughout the year in the Solar-CCHP compared to its share in CCHP-system due to decreasing the capacities and the gas purchased.

A decrease in the amount of the gas purchased by 9.59% as shown in Table 2. is clear especially after the decrease of the ICE capacity and the introduction of solar systems. However, this is not the case in grid electricity. This is because grid electricity compensated the decrease in the ICE share in supplying the electricity and giving a priority for the solar-CCHP to be sold due to its larger selling price.

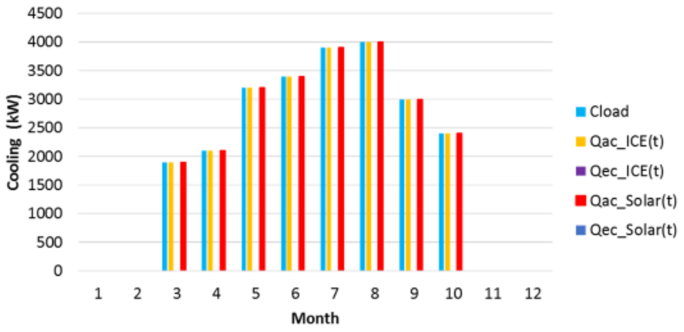

Fig. 6 Optimal scheduling of cooling load (kW)

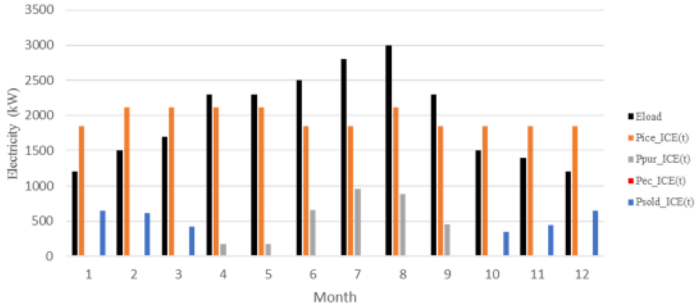

Fig. 7 Optimal scheduling of electrical load in CCHP system

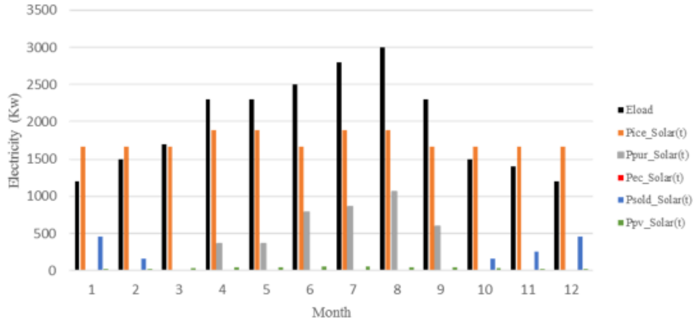

Fig. 8 Optimal scheduling of electrical load in CCHP system

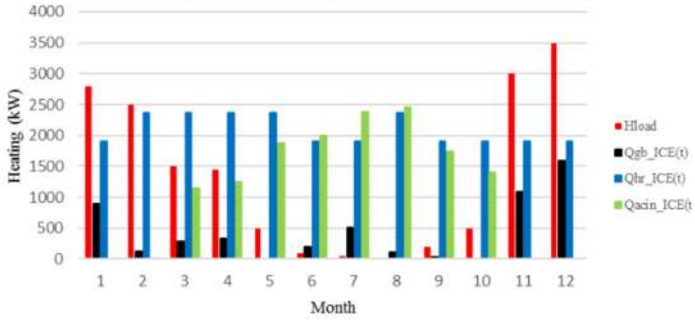

Fig. 9 Optimal scheduling of heating load in CCHP system

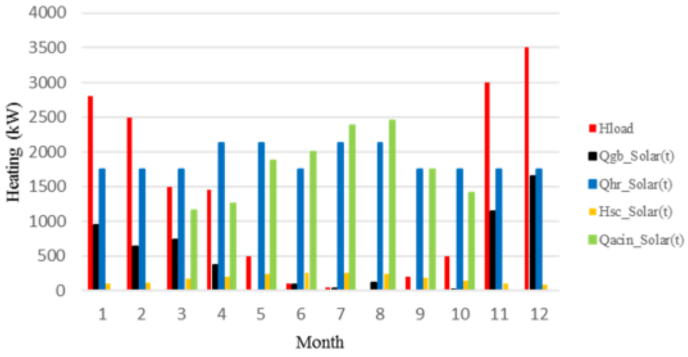

Fig. 10 Optimal scheduling of heating load in Solar-CCHP system

D. KPIs and economic parameters

Adding solar energy components to fill a constrained roof area of a building increased the initial and operating costs. However, the maintenance costs of the CCHP system is greater. This result is expected as increase in capital costs of solar systems is the main obstacle in deployment of solar energy systems in the energy industry.

The operating costs increased by increasing the amount of electricity purchased. The maintenance of the large capacity ICE is usually very expensive and occurs very regularly.

Moreover, the decrease in the capacity of the ICE along with the small share of the PVs in selling expensive solar-electricity has led to less revenues compared to the CCHP system. This led to decreasing the ATCSR by 22.69% of that of the CCHP-system and decreasing the NPV and the IRR by 67.29% and 63.65% respectively. However, by decreasing the gas purchased amount and starting to introduce more renewable solar energy even in small amount, the FSR and the CO2RR have increased by 5.71% and 7.77% respectively. This increase is accompanied by a slight decrease in the exergetic efficiency. At the end of the day, the main parameter that combines all the KPIs is the combined efficiency which has shown an increase of 1.20% in Solar-CCHP system compared to CCHP system.

TABLE II EFFECT OF INTRODUCING SOLAR ENERGY COMPONENTS ON AN OPTIMIZED CCHP SYSTEM.

Parameter	**Increase % of Solar-CCHP system from CCHP system**
ATCSR	-22.69%
FSR	5.71%
CO2RR	7.77%
ETAEX	-0.24%
CE	1.20%
NPV	-67.29%
PBP	51.83%
IRR	-63.65%
P_{ICE}	-11.95%
P_{GB}	9.01%
Q_{HRN}	-10.23%
Gas Purchased (kWh)	-9.59%
Electricity Purchased (kWh)	23.65%

V. CONCLUSION

This paper provides a methodology of real assessment of using solar energy components. This methodology depends on comparing an optimized CCHP system with an internal combustion engine (ICE) as a prime mover and an optimized Solar-CCHP system with the same components of the CCHP systems but with the addition of solar collectors and photovoltaics under a constrained roof area. The novel contribution of this paper is that it provides a system-level comparison methodology that compares the whole system performance not the performance of a single component. Moreover, it deals with the environmental and exergetic aspects of the whole system with optimal planning and scheduling of these systems.

Results showed that the combined efficiency increase percentage of the Solar-CCHP is 1.20% although the ATCSR decrease percentage of the Solar-CCHP system is 22.69%. Moreover, the NPV, IRR and PBP recorded a decreased percentage of 67.29%, 63.65% and -51.83% respectively.

These results assured the importance of comparing energy systems based on the system-comparison methodology as it guarantees more improvement in system performance after allowing the configuration, sizing and scheduling of the original CCHP system to change after the solar intervention to form a polygeneration system

These results also assured the importance of reducing the capital costs of solar energy systems to facilitate their deployment in future energy systems as they already prove their ability to increase overall combined efficiency of energy systems by decreasing the fuel used and emission produced.

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