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Techno-Economic and Life-Cycle Cost Assessment of the CCHP/PV Hybrid System Application

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A B S T R A C T

In recent decades, excessive using fossil fuels has been resulted in emitting greenhouse gases such as CO_2, consequently, environmental pollution. In this study, the techno-economic analysis of the CCHP/PV hybrid system application for a sample building was examined to reduce the environmental pollution and primary energy consumption of the buildings. The life-cycle cost analysis was utilized as a robust economic criterion. To investigate the effect of climate conditions on the system performance, five cities of Bandar Abbas, Ahvaz, Tehran, Bandar Anzali, and Ardebil were considered and evaluated. The results showed that the pollution emission rate and primary energy consumption of the building were declined by the CCHP/PV system up to 10.14 % and 26.52 % for the coldest climates, respectively. Moreover, an increase of 33.33 % was observed compared to the conventional system due to its high initial investment. However, the sensitivity analysis of energy tariffs, as well as equipment prices indicated favorable results and a bright horizon for these systems.

1. INTRODUCTION

Today, energy is a category that may be considered as the most critical issue. Development of industries, especially in recent decades, has led to excessive energy consumption and enhancement of environmental pollution. The end of fossil fuel resources and global warming have resulted in discovering the importance of using alternative energy systems such as combined heat and power (CHP) systems, solar and wind energy. Meanwhile, using photovoltaic panels that directly generate electricity from sunlight is one of the effective ways to diminish air pollution. However, the periodicity of the sun irradiation interrupts the power generation via PV panels due to its absence at night and during cloudy weather [1]. The PV cells can be served in combination with the CHP systems to deal with this problem. The CCHP/ PV hybrid systems are one of the efficient energy options that not only increase the proficiency of the system but also eliminate the periodicity of the power produced by the PV panels. The CHP systems are interesting for many international organizations due to such benefits including improvement of energy efficiency, safe heat supply and flexibility, reduced environmental pollution, and increased effectiveness. On the other hand, the buildings are known as a significant potential sector for using such systems. At present, about 35 % of the world's total energy consumption is used in the buildings [2]. In this regard, there are a large number of research works in recent years in which using such systems has been investigated in the different sectors. These studies mostly scrutinized the optimization of the CHP and CCHP systems. For example, Ameri and Besharati [3] have developed a mixed integer linear programming (MILP) model to determine the optimal capacity and utilization of 7 CCHP systems in a heating and cooling network located in the east of Tehran. They showed that using an optimally integrated CCHP system with photovoltaic panels, a reduction of 40.8 % and 38.7 % for energy costs and primary energy consumption are accessible, respectively. Cho et al. [4] have presented the feasibility design and analysis of a CHP integrated system with a heat pump (HP) for residential applications. The results showed that the proposed CHP-HP system is applicable in the cold weather regions. Mago and Chamra [5] using a CCHP system have analyzed and optimized a sample building with particular attention to energy, economic and environmental issues. They analyzed and optimized various CCHP operational strategies based on several optimization criteria such as reducing operating costs, saving energy, and minimizing (detrimental) environmental impacts. The results indicated that the operating CCHP systems having just one optimization

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criteria provide better performance than the CCHP systems without any of them. Zhang and co-workers [6] have investigated the Micro-grids design with CHP units regarding their economic and environmental sustainability in a multi-objective optimization model. They also presented a life-cycle assessment for the surveyed micro-grids. The results disclosed that the installation of the several CHP systems, which are properly situated, causes lower costs as well as better environmental performance than when using just one CHP system. Numerous studies have also focused on solar-wind hybrid systems [7-12]. However, in recent years, few studies have been carried out about the combination of the CHP systems with solar systems. It is worthy to note that Wang et al. [13] have proposed a life-cycle optimization method in order to improve the CCHP system with Solar Energy for minimizing its environmental impact during its life-cycle. The motivation for this study was to optimize the life-cycle performance of a hybrid CCHP system with solar energy and natural gas. Furthermore, Rodriguez et al. [14] have evaluated the performance of different designs of hybrid systems related to the solar collectors/photovoltaic panels and internal combustion engines (ICE) with natural gas. Besides a comprehensive analysis of life-cycle costs, pollution emissions and primary energy consumption have been also presented. Their results exposed that the conventional design has the least life-cycle cost among all the other studied hybrid designs. Ondeck et al. [15] have also investigated the optimal performance of the hybrid PV/CHP system for a residential area as well as the impact of integrating CHP plants with solar cells. They found that this system not only can cover the entire electricity, heating and cooling requirements but also has some advantages because of selling excess electricity to the grid in times that its supply is difficult. it should be mentioned that the optimal size for the Micro CHP-Solar hybrid system for the household sector has been provided by Brandoni and Renzi [16]. Their results showed that the optimum size of renewable hybrid systems has a significant effect on maximizing energy and economic savings compared to conventional production. Moreover, Pearce [17] has examined the PV/CHP hybrid system for a residential building to overcome the challenges of the electricity generation periodicity through the photovoltaic arrays. This study revealed that the hybrid PV/CHP system overwhelms the inherent challenges of the PV electricity periodicity. Shah et al. [18] have conducted an investigation on the operation of the PV/CHP/battery hybrid energy systems. They demonstrated the technical capabilities of such systems and simulated a PV/CHP/battery hybrid system on a household scale in three regions in the United States using a mixed optimization model for renewable power. Their results showed that the generated electricity from each component of the hybrid system can fully satisfy the load demand for the residential building. The other investigation which has been implemented by Kim et al. [19] showed the effect of using the CCHP and CCHP/PV systems on the primary energy consumption and economic and environmental aspects in a sample building in Atlanta. In this research, simulation of the systems was performed via HOMER software. It indicated that the combination of micro-turbines with absorbing chillers and PV can make a considerable reduction in the supplied energy from the power grid in power consumption peak times.

The main goal of this research is to provide a techno-economic analysis using the hybrid CCHP/PV system for a sample building in Iran to lessen the primary energy consumption and environmental pollution. A major part of the building's electricity demand is supplied by gas-fired internal combustion engines and photovoltaic panels mounted on its ceiling. It is also possible to sell the photovoltaic electricity to the grid, so, the system is connected to it. Unlike the aforementioned research works, this current one also considers the effect of the climate conditions on the system performance. To inspect the climate effects on the system's efficiency, five cities (BandarAbbas, Ahvaz, Tehran, BandarAnzali and Ardebil) having different climates were selected. Life-cycle cost analysis was also conducted as a robust economic criterion. In the last section, a sensitivity analysis of the costs and equipment was presented. Finally, HOMER software was applied to execute all the simulations.

2. PROCEDURE: STUDY CHARACTRISTIC

2.1. Building and weather

The analyzed building in this research is a 7th-floor residential block. It has an east-south view and an infrastructure of $1050m^2$. The substructure of each floor is $150m^2$ and there is a building unit on each floor. The study was conducted for five different geographical locations of Iran (BandarAbbas, Ahvaz, Tehran, BandarAnzali, and Ardabil) and weather data including temperature, solar radiation rate, and network water temperature were provided for each location. The building characteristics are shown in Table 1.

Table 1. The building characteristics.

Frontage	East-south
Building type	Residential
Area (each unit)	$150m^2(15m \times 10m)$
Total area	$1050m^2(7 \times 150m^2)$
Glass area	30% in each wall (windows and door)
People	28
Lights	11480 W

2.2. Building energy requirements

2.2.1. Estimation of the electricity demand

The electricity demand of a building is estimated established upon the definition of specific equipment and their power and average daily consumptions for a residential home in Iran.

For a residential unit, Table 2 presents the electrical consumers [20].

Table 2. Electric consumers for a residential unit.

Consumer device	Power (W)
Light	1640
LCD TV	200
Refrigerator	300
Computer	250
Vacuum cleaner	1300
Washing machine	2500
Dishwasher	2000
Iron	1100
Hairdryer	1200

For each consumer, the following assumptions are considered:

• The operating hour of the lighting system is determined according to each month of the year and sunset time.

• For items such as iron, vacuum cleaner, and hairdryer, which are utilized based on a weekly basis, the average daily contribution is considered. Finally, the average daily consumption pattern for the 7^{th}-floor building block is generalized. The total daily load profile for the building is shown in Table 3.

Table 3. Daily load profiles of the building.

Average daily energy consumption	$136\ kWh/day$
Average power consumption	$5.67\ kW$
Power Consumption Max	$32.6\ kW$

2.2.2. Calculation of thermal and cooling load

The demand for heating and cooling of the building varies according to its geographic location. Energy Plus software was used to obtain the demand quantities. Moreover, this demand for domestic hot water (DHW) was calculated using the Iranian standard. Monthly load demand for Tehran is shown in Fig. 1 (similar charts were acquired for the other areas). Furthermore, the summary of the annual demand for electricity, heating, cooling, and DHW is presented in Table 4 for each climate zone.

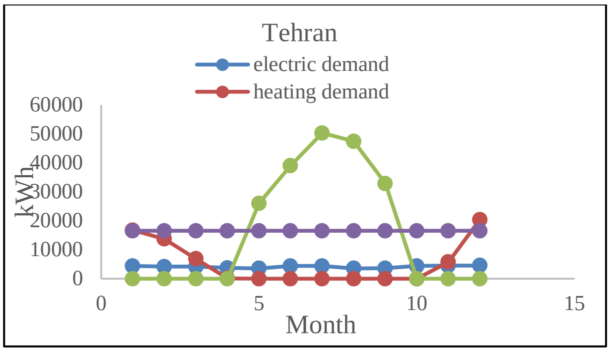

Figure 1. Monthly load of electricity, heating, cooling and hot water consumption for Tehran**.**

Table 4. The annual demand for electricity, heating, cooling and hot water consumption for the different climates.

Location	DHW demand $\left(\frac{kW\,h}{m^2}\right)$	Heating demand $\left(\frac{kW\,h}{m^2}\right)$	Electricity demand $\left(\frac{kW\,h}{m^2}\right)$	Cooling demand $\left(\frac{kW\,h}{m^2}\right)$
Bandar Abbas	189.26	0.37	47.5	556.74
Ahvaz	189.26	6.06	47.5	376
Tehran	189.26	60.7	47.5	186.3
Bandar Anzali	189.26	25	47.5	154
Ardebil	189.26	141	47.5	68.8

3. THE SYSTEM SIMULATION

In this section, the CCHP/PV hybrid system containing PV panels and GFICE for a sample building is studied and simulated. HOMER software was used to execute all the simulations.

3.1. Homer

Besides the simulation implemented by the HOMER software, it is used to evaluate the techno-economic issues related to the hybrid energy systems including wind turbines, fuel cells, hydropower, biomass, batteries, converters, photovoltaic panels, and CHP systems. It should be mentioned that this software has been developed by the US National Renewable Energy Laboratory (NREL). The HOMER software simulates the function of the system by energy balance calculations for every 8760 hours of the year [21]. Using input data, it examines all possible configurations for the renewable Micro-grid systems and arranges top configurations based on the lowest net present cost (NPC) as the optimal mode. NPC calculations are presented as follows [21]:

$$NPC = \sum_{0}^{T} (C_{Cap,t} + C_{OM,t} + C_{Replace,t} + C_{Fuel,t} - R_{Salvage,t}) \quad (1)$$

where T denotes the lifetime of the project, $C_{Cap,t}$ is the current value of the investment costs for the year t, $C_{OM,t}$ is the current operating and maintenance cost for the year t, $C_{Fuel,t}$ is the current value of fuel costs for the year t, $C_{Replace,t}$ is the current value of the replacement costs for the year t and $R_{Salvage,t}$ is the current value of the recycled price for the year t.

3.2. Simulation of the CCHP/PV hybrid system

The proposed hybrid system is composed of the solar PV panels and gas-fired generators that defines and models the internal combustion engines, converters, auxiliary boilers, and power grids.

The gas-fired internal combustion engines supply a significant part of the electricity prerequisites of the building, also, the remaining electricity requirement is provided by the photovoltaic panels and electricity grid.

As well, the heating requirements with respect to the building are provided using wasted heat recycling of the engines and with an auxiliary boiler. The surplus electricity produced from the photovoltaic panels is also sold to the grid. The cooling demand is also satisfied by the chillers that work with the electricity.

The HOMER software ultimately chooses the best optimal mode economically (See Fig. 2) by inspecting all the connections between the various components of the system. Additionally, the economic data governing the project are presented in Table 5.

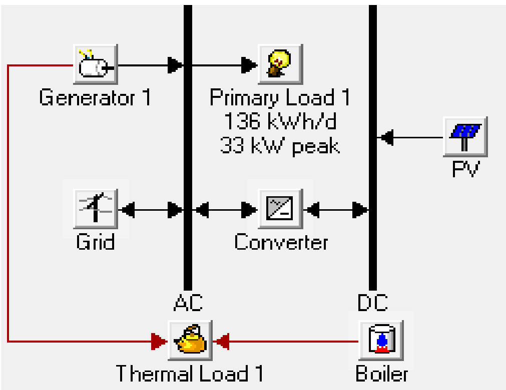

Figure 2. Schematic of the hybrid system.

Table 5. The economic data [22-24].

Lifetime of the project	25 yr
Interest rate	%15
The price of the electricity purchases from the grid	0.095 $\$/kWh$
The price of the natural gas	0.14 $\$/m^3$
The photovoltaic power sale price to the grid	0.235 $\$/kWh$

3.2.1. The operating protocol

Due to the results obtained from the software, by analyzing and simulating the hybrid system, the optimal mode according to the least NPC was obtained as follows:

• Three 5 kW gas-fired internal combustion engines are used to respond to a part of the electricity needs of the building. The engines function separately and to prevent operation of the engines at their minimum power (with high fuel consumption), they are only turned on when the instantaneous power demand exceeds 30% of the engine's power. Otherwise, the electricity will be taken from the grid.
• 50 Solar Panels of the ASM6610P-260 model (with a total capacity of 13 kW) are inserted on the roof of the building. Since the electricity generated from the photovoltaic arrays is without environmental pollution, the consuming electricity cost for the household will be expensive. Therefore, in the economic analysis of the system, the lowest NPC is obtained where most of the generated electricity from the photovoltaic arrays is sold to the grid. Please note that in the Iranian grid, the electricity cost supplied by the grid is low-priced. However, the government purchases the electricity produced by renewable energies at desirable rates. The simulation results showed that only a small amount (2.08 kW) should be used to respond to the electricity demand of the building.
• Two 1kW converters are considered in order to convert the DC generated by the panels to the AC.
• The heat produced by engines in the electricity generating process is used to reduce the required energy for the boiler.
• The cooling system consists of a condensing chiller whose cooling capacity varies depending on the climatic zone. In the current research, the chillers were launched by the power grid.

The initial investment, maintenance, replacement and component lifetime costs are presented in Table 6.

4. RESULTS AND DISCUSSION

In the previous sections, the CCHP/PV hybrid system was simulated and the best mode for the lowest net present cost was selected. Moreover, the electricity and heating costs of the building, as well as the investment and operating costs of the system were obtained. In this section, we will consider the amount of primary energy consumption, emission, and the cost analysis of the system life-cycle.

4.1. Calculation of the primary energy consumption of the building

In this section, the amount of annual primary energy consumption for the surveyed cities is presented. In the

CCHP/PV hybrid system, when the conventional system is used, a comparison based on the primary energy consumption is carried out (all the electrical energy and entire heat are obtained from the grid and boiler, respectively). The primary energy consumption factors (gained from [14]) are considered as follows:

Primary energy consumption factor of the power grid: 2.35 $\left(\frac{kWh}{kWh}\right)$

Primary energy consumption factor of the natural gas: 1.07 $\left(\frac{kWh}{kWh}\right)$

Table 6. The costs and lifetime of system components.

component (yr)	Initial investment cost $(\$/yr)$	Replacement cost $(\$/kW)$	Maintenance cost $(\$/kW)$	Lifetime (yr)
PV panel [25]	808	808	12	25
ICE [26]	2900	2610	888	15
Converter [27]	600	600	0	15

Annual primary energy consumption for the CCHP/PV system and the conventional one are presented in Fig. 3.

As it can be seen, using the CCHP/PV hybrid system significantly results in the reduction of the primary energy consumption of the building in all climatic regions. In the hot climate regions (Bandar Abbas), primary energy consumption is high due to the chiller consumption, while in the cooler ones, there is a further reduction in the heating costs because of its recycling from the engines. For a complex residential area that includes 100 blocks of seven floors, this system can be saved about 16.33 GWh energy per year.

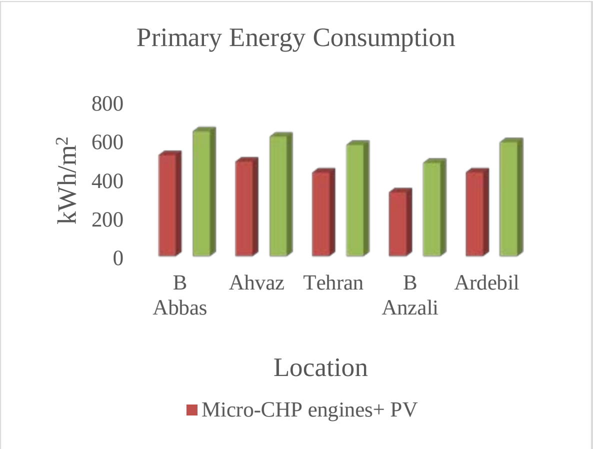

Figure 3. Annual primary energy consumption for the CCHP/PV and conventional systems.

4.2. Evaluating the environmental pollution emission rate

One of the major goals of this research is to evaluate the emission reduction rate of CO_2 during using the CCHP/PV hybrid system. The pollution emission factor (obtained from [14, 19]) is considered as follows:

Table 7. The pollution emission factor in natural gas.

Carbon monoxide $\left(\frac{gr}{m^3}\right)$	6.5
Unburned hydrocarbons $\left(\frac{gr}{m^3}\right)$	0.72
Particulate matter $\left(\frac{gr}{m^3}\right)$	0.49
Nitrogen oxides $\left(\frac{gr}{m^3}\right)$	58

The pollution emission factor in the power grid is equal to 649 gr CO_2 /kWh.

The annual CO_2 emission for the CCHP/PV and conventional systems are presented in Fig. 4.

According to the results, the CCHP/PV hybrid system has less pollution in all areas than the conventional one because of its lower use of electricity from the grid. When we deal with 100 building blocks, using this system for each building block leads to reducing the annual emissions of CO_2 up to 1500 tons.

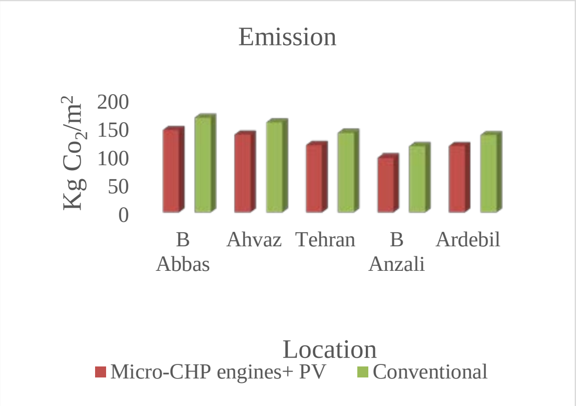

Figure 4. Annual CO_2 emission for the CCHP / PV and conventional systems.

4.3. Cost analysis of system life-cycle

The life-cycle cost assessment (LCC) covers all the cost components and also considers the benefits and revenues in evaluating solutions. Based on the life-cycle cost assessment, the economic value of the CCHP/PV hybrid system is estimated in the studied building. Therefore, the following equation is utilized [14]:

$$LCC = Initial_{investment} + Costs_{replacement} + (Costs_{operation} + Costs_{maintenance}) \cdot \sum_{t=1}^{25} \frac{1}{(1+r)^t} \qquad (2)$$

In this case, t and r denote the year and interest rate, correspondingly. The interest rate is assumed to be 15 %. The life-cycle cost analysis for the CCHP/PV and conventional systems are illustrated in Fig. 5.

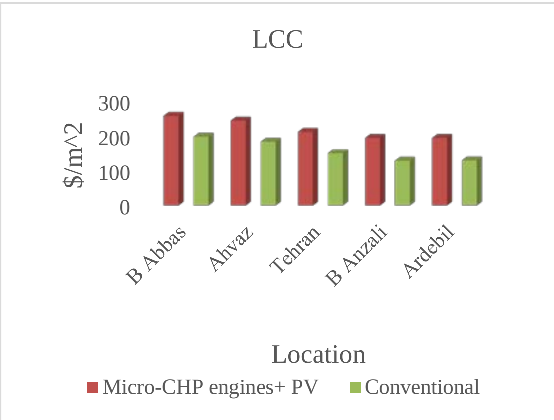

Figure 5. Annual life-cycle cost for the CCHP/PV system and conventional systems.

Given the results, it is clear that the life-cycle cost in the warmer regions is more than cold ones due to the higher operating costs and an initial investment of the equipment (e.g. chiller). Besides, since the CCHP/PV system regarding the primary energy consumption and environmental pollution emissions compared to the conventional system is the best, owing to the high initial investment costs and replacement of the equipment, these costs may not be compensated by the energy savings. Hence, the conventional energy system is superior to the CCHP/PV system economically, which is due to the lower gas and electricity tariffs in Iran as well as the relatively high investment costs for the gas-fired internal combustion engines. However, it is predicted that the CCHP/PV system exposes a new window with respect to the energy prospects very soon. It can be feasible with the development and mass production of these engines and the reduction in their investment costs. The comparison of the current research work with the other ones, e.g. Rodriguez et al. [14], confirms our results. The results of both studies indicate that using the CCHP/PV system significantly decreases the primary energy consumption and CO_2 emissions. Nevertheless, due to the initial investment costs, it is not economical.

5. SENSITIVITY ANALYSIS

A sensitivity analysis of a design is a review of the economic evaluation implemented by changing its initial parameters. In this section, we investigate the sensitivity analysis of the energy, panel and engine costs and interest rates through defining different scenarios. Due to the similarity of the results, Tehran was selected as a prototype.

5.1. Sensitivity analysis of panel cost

Due to decreasing the panel cost, at first, the sensitivity analysis of the investment cost in the PV panels was carried out. The results showed that by reducing the investment cost of the panels, there is no significant decline in the life-cycle cost of the studied system because sharing the investment cost of the panels is very low relative to the whole system (mainly based on the high cost of the engines). The results of Tehran are shown in Fig. 6.

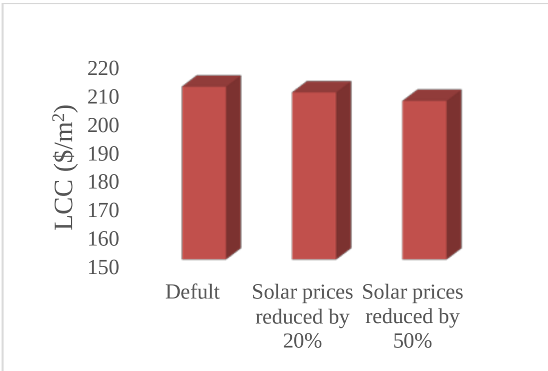

Figure 6. The effect of the solar panel cost on the system life-cycle cost.

5.2. Sensitivity analysis of the energy tariffs, interest rates, and engine costs

In this section, the impact of operating costs is examined with considering the enhancement of the energy tariffs cost (electricity and gas), as well as reduction of the engine costs and interest rates. Sensitivity analysis was performed with the scenarios having different costs for all climatic regions (see Table 9). Since the results were very similar for all regions, so, the results are only described for Tehran (see Fig. 7).

According to the presented results, the increase in the power grid tariffs without changing the natural gas tariff is led to the CCHP/PV system being more economical, so that, in the sixth scenario, the life-cycle cost of the current system is even higher than the hybrid system. The reason is that the conventional system receives all its electricity from the grid while the CCHP/PV system supplies a significant part of its electricity from the gas-fired internal combustion engines and panels. These seven scenarios show that increasing the natural gas tariffs with fixing electricity tariffs destabilizes the profitability of the hybrid system due to using the natural gas in the engines.

Table 8. The price scenario.

Price Scenario	EL Price ($/kWh)	Price ($/kWh) NG	r (inflation rate%)	Price ($/kW) Engines
S1	0.095	0.14	15	2900
S2	0.1425	0.14	15	2900
S3	0.19	0.14	15	2900
S4	0.2375	0.14	15	2900
S5	0.285	0.14	15	2900
S6	0.38	0.14	15	2900
S7	0.095	0.28	15	2900
S8	0.19	0.28	15	2900
S9	0.38	0.42	15	2900
S10	0.38	0.56	15	2900
S11	0.19	0.14	10	2320
S12	0.19	0.14	10	1450
S13	0.285	0.14	10	1450
S14	0.19	0.14	5	2320
S15	0.19	0.14	5	1450
S16	0.285	0.14	5	1450

The other scenarios also examine the impact of variations in the interest rates and investment cost in the engines, as, for example, decreasing the interest rates results in the higher profitability of the hybrid system and weakening the conventional one. Furthermore, the reduction in the investment costs of the engine leads to that the CCHP/PV system becomes a more economical system.

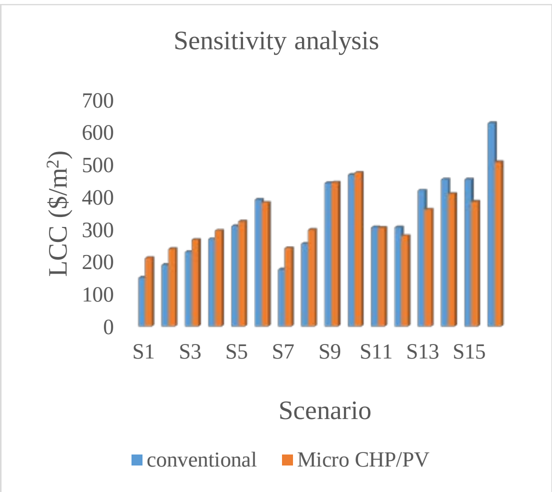

Figure 7. Life-cycle cost for the CCHP/PV and conventional system in different scenarios.

6. CONCLUSIONS

In this research, the techno-economic analysis of the CCHP/PV hybrid system application in a sample building for five cities having different climates in Iran with the purpose of reducing the primary energy consumption and environmental pollution emission was carried out. The LCC assessment was presented as an economic criterion. The results of life-cycle cost estimates for the coldest region (Ardebil) showed that using the CCHP/PV system, we encounter to a cost increase of 33.33 % compared to when the conventional system is utilized. Therefore, the conventional system is economically desirable than the CCHP/PV system. Moreover, the CCHP/PV hybrid system reduced the primary energy consumption by 26.52 % compared to the conventional system. So, for a residential complex that includes 100 blocks of seven floors, this system saved about 16.33 GWh per year. Besides, the results indicated that using the CCHP/PV hybrid system results in decreasing the environmental pollutants emission. Finally, the sensitivity analysis of energy and equipment costs showed very favorable outcomes. Therefore, with lowering the investment costs of these systems, also, an increase in the energy tariffs cost due to the shortage of the fossil fuels and concerns about global warming, one can imagine a special place for these systems in the energy sector.

7. ACKNOWLEDGMENT

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