Techno-economic comparative study of hybrid microgrids in eight climate zones of Iran

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Abstract

Many efforts have been made to increase the utilization of renewable energy resources (RESs) in Iran. This paper aimed to evaluate the techno-economic performance of an introduced hybrid microgrid (HMG) in eight climate zones of Iran. Therefore, ten cities are selected from the eight climate conditions of Iran. An electricity pricing strategy is also implemented according to the electricity tariffs defined by the Ministry of Energy (MOE) of Iran. The proposed electricity pricing strategy is applied to the HOMER software for investigating the optimal system configuration, RES electricity generation, and the economics of each understudy city. Optimization results indicate that Urmia (in moderate and rainy climate zone) has the least net present cost (NPC) (−5839$) and levelized cost of energy (COE) (−0.0122 $/kWh), whereas Golestan (in semimoderate and rainy climate zone) has the highest NPC (4520 $) and COE (0.012 $/kWh). It is shown that the combination of photovoltaic (PV)/wind turbine (WT)/converter in the grid-connected operation mode is the most economical configuration. Moreover, the cities with higher potentials of wind speed and solar irradiance have lower NPC and COE. It is concluded that the utilization of the battery energy storage (BES) is technically and economically infeasible for all eight climate zones, even if the stored electricity is sold to the grid. Two sensitivity analyses are conducted to the electricity feed-in-tariff (FiT) and solar module price, respectively. The first sensitivity analysis indicates that by increasing FiT, more contribution of RESs is seen, which leads to lower COE and NPC. Furthermore, the two cities of Urmia and Yazd have the highest NPC and COE reductions. The second sensitivity analysis studies the module price impacts on the NPC and COE of each understudy city. It is revealed that the PV module price has a considerable effect on NPC and COE. However, this effect is more significant in some cities such as Bam, where a linear relationship is seen between the module price and economic results (NPC and COE).

KEYWORDS

battery energy storage, cost of energy (COE), electricity tariffs, hybrid microgrids (HMGs), net present cost (NPC), photovoltaic (PV), wind turbine (WT)
1 | INTRODUCTION

The Middle East is one of the most significant energy resources of the world, and thus, the price of fossil fuels is low in comparison with the world’s average. However, Middle Eastern countries are gravitating toward renewable energy resources (RESs), specifically by the increasing demand for electricity in this region. As a Middle Eastern country, Iran is going with the same trend in the energy consumption rate, which is due to government paid subsidies on fuels.1,2

The need for energy is growing each day as the world population is increasing, and the industries are developing.3 The continuity of available fossil fuel consumption trend releases a considerable amount of emissions, which impose significant risks on the environment.4 On the other hand, the resources of fossil fuels are limited and nonrenewable.5 Moreover, nuclear energy would not be a proper option because of its controversial waste disposal and corresponding risks to the environment. Therefore, sustainable clean alternatives with low production cost would be of great importance.6

Renewable energy industries are the world’s fastest-growing ones due to the significant development of the global clean energy sector.7,8 More than 30 countries in the world provide over 20% of their total energy by RESs.9 It is believed that the produced energy from RESs exceeds the amount produced by natural gas or nuclear facilities. It is also estimated that by the end of 2040, renewable energies become the dominant source of energy production. Moreover, it is estimated that the energy production of RESs rises from 4.73 TWh in 2012 to 10.63 TWh in 2040 due to improvements in efficiencies and availability of these resources.10

The geography and the specific climate of Iran made it suitable for different means of renewable energy production. The southern region of the country is located on the world’s “Sun-Belt,” which is the world’s most irradiation receiving from the sun (4.5-5.5 kWh/m² by direct nominal irradiation). The country has almost an average of 300 sunny days per year.11 In the researchers’ estimation, Iran has around 20 GW wind power capacities. However, more than 70% of the consumed energy is generated by fossil fuel power plants. Iran is one of the key players of the oil supplying countries in the world. However, increasing national energy demand has affected the export volume of oil to keep up with the demand of the country. Iranian authorities have taken proper steps to increase nonhydroelectricity generations up to 2000 MWh by the end of 2025. Furthermore, to meet the universal movement of reducing the production of greenhouse gases, Iran is pledged to decrease up to 4% of greenhouse emissions by 2030.12

The government in Iran is looking for a substitute for electricity generation sources other than the hydrocarbons.13 By doing so, conserved natural resources can be utilized elsewhere instead of turning to electricity generation that would be more cost-efficient. The Iranian government is now fully aware of the potential of RESs and little by little preparing the required infrastructures and providing tariffs to attract private sectors for investment. The country announced to reach up to 5000 MW of renewable energy generation by the end of 2015, according to the 5th Development Plan. However, this aim was not fulfilled due to imposed economic sanctions and the lack of infrastructures in the renewable energy section. Afterward, the sixth development plan was approved by the parliament to reach this goal by the end of 2021 and 2500 MW more by the end of 2030. It is estimated that 10% of the country’s electricity requirement could be provided by RESs in the next 5 years.13

One of the technical ways to increase the usage of RESs in distributed sizes is the utilization of hybrid microgrids (HMGs) in power systems. HMGs are usually equipped with RESs and storage systems such as batteries and can work in two different operating modes, namely grid-connected and off-grid. HMGs have various technical and economic advantages over conventional consumers. In grid-connected mode, HMGs can sell extra generated electricity by RESs to the utility grid, which would bring financial benefits to the system. HMGs can operate in islanding mode during grid outages, which increases the system reliability. Also, the off-grid operating mode is a suitable choice for rural areas, which have not been connected to the electric distribution systems.14

The hybrid energy storage and HMG have been recently received significant consideration from researchers.15 As an example, authors in16 designed an optimal HMG, including WT, PV, and traditional energy resources for a remote rural area located in West Africa. Based on the results of,16 it is evident that they achieved a noticeable reduction in economic and environmental costs. Furthermore, in,17 novel optimal scheduling has been suggested to minimize the operating cost of a stand-alone microgrid. The MG’s model has been transformed into mixed-integer linear programming (MILP) and then solved by applying the CPLEX solver. Their proposed strategy had better results than other similar previous works. However, the transformation from a real model into a linear model was not practical for any component and system. Also, it might result in errors in analytical analyses.

One of the interesting objectives in recent studies is analyzing the optimal system configuration by economic aspects such as net present cost (NPC) and the cost of energy (COE). Hence, the optimal system has a minimum of NPC and COE.18 In the literature, there are several studies aimed for the optimal design of HMGs, which benefit from RESs in different regions of the world, especially in developing countries.19,22 Authors of19 proposed two different energy systems in two locations of Sabah, Malaysia. The first energy system included PV/diesel generator (DG)/BES and converter, while the second introduced system was merely based on PV/BES. By using HOMER software, the optimization of each energy
system has been done to achieve the minimum NPC and COE. It was concluded that the first energy system, which was defined based on hybrid PV/DG/BES and converter, had the best techno-economic performance. However, the PV-based system was much more environmentally friendly than the first energy system. The sensitivity analysis of fuel price and load demand showed that the increase in these two parameters leads to change trends toward the use of PV/DG and BES.

Moreover, a decrease in BES and PV costs results in the lower NPC and COE and more contribution to these resources in the optimal system. Since the considered energy systems are stand-alone, the utilization of BES resulted in active operation during the planning horizon. In, the effect of integration of the utility grid on the optimization results has not been studied. The integration of the utility grid may change the technical-economic results, especially the feasibility of BES.

Another study investigated a stand-alone microgrid in the South China Sea, Malaysia. The optimum configuration consisted of PV/WT/BES and converter, which was similar to the previous study in. Simulation results indicated that the combination of PV/WT/BES and converter would result in better NPC and COE compared to the DG-based energy system. However, the authors did not propose any sensitivity analysis of optimization parameters. The sensitivity analysis of fuel cost or PV module price illustrated the other aspects of the optimization results.

In another developing country, Nigeria, the authors proposed an optimal configuration based on the NPC and COE, which included the PV/DG/BES and converter. The sensitivity analysis also showed that using WT in the hybrid system was not economically feasible because the potential of wind speed was low in the understudy site.

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In, the economic, reliability, and environmental benefits of RESs in an HMG were investigated. The HMG included the PV, WT, BES, and DG. This research aimed to minimize the value of COE, annual cost, and life cycle cost. The six scenarios have been presented for evaluating the performance of the proposed strategy. The given results illustrated that the cost metrics mentioned above were considerably reduced by their proposed strategy. In, HOMER was employed for an economic feasibility study of a PV system in a grid-connected semiconductor facility in South Korea. It was exhibited that PV/grid and PV/BES/grid were more viable than grid-tied systems if the grid costs were increased and PV costs were reduced. In another study, which was performed in Wellington, New Zealand, the 10-kW grid-tied PV system installed in Maungaraki school was analyzes based on performance and economic value based on the NPV (net present value), COE, and the simple payback period.

In addition to the aforementioned reviewed papers, some researchers studied HMGs in different climate zones. In this kind of researches, different climate zones with their specific weather conditions and RES potentials were investigated to find the optimal configurations. It is worth noticing that these types of studies have not been appropriately considered in developing countries. Here, some of the recent papers in this field of research are reviewed.

In a recent research paper, eight climate zones in the United States were studied for analyzing the potential of each climate zone for HMGs. The mentioned paper investigated small commercial buildings using stand-alone HMGs. Moreover, a homemade tool has been implemented in MATLAB/Simulink to model a poly generation powerplant working in a stand-alone condition for a mall in the United States. The results have also been compared with those of HOMER. Their investigation revealed that in cities such as Houston, Miami, or Las Vegas, where average temperature and daily solar irradiation are in the most favorable state, it was not reasonable to operate the system in grid-connected operating mode. Simulation results confirmed that the use of BES was not economic in the optimal grid-connected system. Furthermore, the emission was reduced by using PV/grid and PV/grid/BES. The sensitivity analysis indicated that an increase in inverter rate would increase NPC and COE.

Researchers of investigated the feasibility of WT/PV/BES HMGs in five regions of Morocco. The test results showed that the WT existed in all regions except the eastern region, which its wind potential was not appropriate. This exclusion consequently increased NPC and COE of the system and decreased renewable fraction (RF) of the system in that specific region. In, the rooftop PV equipped houses of fourteen families in five regions with different climates in China were studied in the grid-connected operating mode. It was conducted that the region with a mild climate, namely Kunming, was the best place for the PV/grid system. In, HOMER software was used to analyze the impacts of the component costs, carbon taxes, and feed-in tariffs on grid-connected PV systems in the Malaysian residual sector. Their results revealed that the grid-connected PV system was highly feasible by PV array costs of 1120 $/kW or less. In, the feasibility of the grid-tied PV system for three buildings in New Delhi, India, was evaluated by using HOMER. It was showed that battery-less grid-connected PV systems were technically and economically favorable.

Some studies have also evaluated HMGs in a few regions of Iran. In, HMGs, including PV/WT/DG and BES, were studied for its electricity supply feasibility in three cities of Iran as Tehran, Binalood, and Kish island with distinct climates. The fuel cost impact on the system was also evaluated by considering two different types of fuel. HOMER was employed for economic analysis, and the results depicted that the ideal region for the HMG was in the Kish island with a very hot and humid climate condition. Another study in Kermanshah, Iran, examined the
economic potential of HMGs, including PV/WT/DG/BES/converter and grid. HOMER results showed that the optimal configuration is DG/BES/converter and grid. In, the potential of four climates of Iran was investigated, and results illustrated that using PV-based system in all climates results in lower COE and NPC. However, the paper did not perform any sensitivity analysis to investigate the impacts of different parameters on the optimum results. In, the authors investigated the potential of multi-energy systems in three different climates of Iran. Simulations have shown that the contribution of PV is more in Hamedan with cold weather than Ahvaz and Tehran with hot weather. However, the study did not present any comprehensive results and investigations of RES productions.

It is worth noticing that in the literature, there have been no extensive techno-economic studies on the optimal design of HMGs in different climatic conditions of Iran, and previous research is limited to certain cities and climates. To fill the mentioned research gap, different climatic conditions of Iran, which are divided into eight climate zones, are investigated. The optimal HMG system is proposed for each city with the lowest NPC and COE according to the climatic conditions. In addition, in previous studies, the electricity purchase rate of the grid has been considered as a single price rate or simple time of use (TOU) rates all over the year. In this study, the real-world electricity rates were applied according to the daily and seasonal variable rates defined by the MOE of Iran. In some of the previous studies, economic parameters such as interest rate and inflation rate have not been applied based on the reality of the Iranian economy. This study tries to implement the optimization problem based on realistic data. A comparison with recently published works also has been provided in the discussion section. The main contributions of this study are summarized as follows.

- The comprehensive research on the potential of RESs in eight climates of Iran has been performed. Moreover, the best economic HMG configuration for each climate has been proposed, which was not applied in.
- A strategy has been proposed to implement electricity tariffs defined by MOE for individual cities and climates based on their weather categories. This approach was overlooked in recent studies.
- The economic feasibility of BESs has been investigated for different climate zones by assuming the possibility of selling electricity from BES to the grid.
- The sensitivity analysis has been performed to get insight into how the PV module price affects the HMGs’ NPC and COE for the different cities in Iran.
- The sensitivity analysis is performed to investigate the impacts of increased FiT on the HMGs’ NPC and COE in understudy climate zones.

2 | METHODOLOGY

2.1 | Simulation tools

In order to study renewable energy systems, there is plenty of software available on the market. Each of them is designated to study a distinct feature of the system. These features are categorized into four categories, prefeasibility (eg, RETScreen), open architecture (eg, TRNSYS), simulation (eg, HYBRID2), and techno-economic and optimization (eg, HOMER).

The prefeasibility study tool, RETScreen, compares the conventional and renewable energy generation projects from the cost and benefits point of view. However, this tool lacks a function for optimization.

The simulation tool, HYBRID2, assesses the performance of renewable-based energy systems using both statistical and time series methods. In spite of the fact that HYBRID2 has high precision in simulations, it is not possible to optimize the aforementioned systems. TRNSYS is one of the most popular tools in thermal and electrical systems for open-architecture simulation. However, TRNSYS is not designed for optimization and is not a user-friendly tool. It also requires professional technology to use it accurately. As it is evident, none of RETScreen, HYBRID2, and TRNSYS tools helps find the optimal configuration and techno-economic analyses of HMGs.

In order to perform the optimization of HMGs’ configuration, techno-economic and sensitivity analysis of both the off-grid and on-grid renewable energy systems, HOMER Pro (version 3.11) developed by National Renewable Energy Laboratory (NREL) is utilized. In this version, inputs such as meteorological data for the regions, technological options, cost of the components, and load profiles are used for simulating different system configurations. HOMER operates in a way that different system configurations are simulated first, and then, the most feasible one based on the objective function is selected. HOMER takes the system constrains into account to present the ideal configuration as well as the minimum total NPC. These constraints are batteries’ charging and discharging control, power balance, etc. The HOMER optimization framework flowchart is shown in Figure 1.

In the HOMER simulation process, economics plays a crucial role in both reaching the minimum NPC and finding the optimum system configuration based on the minimum NPC. The life cycle cost is a suitable parameter with which economics of different configurations are compared. HOMER utilizes NPC to represent the life cycle cost of the system.

The cost of nonrenewable sources and RESs are inherently different. Renewable energy facilities require a considerable capital cost. In contrast, nonrenewable energy sources usually initiate with a less amount of capital cost. However, operating
costs cannot be undermined in nonrenewable-based energy systems. HOMER tends to draw a comparison between the economics of various system configurations, including renewable and nonrenewable energy sources. As mentioned before, HOMER uses NPC to present the life cycle cost of the system. The NPC considers all the costs and revenues into one lump sum according to the date currency in USD with the future cash flows discounting back to the present by the discount rate. Afterward, the project lifetime and the discount rate are specified in the software. The NPC consists of initial purchases of the components, replacement of components, maintenance, fuel costs, as well as the cost of purchasing power from the grid and miscellaneous costs such as penalties from the government for environmental concerns.

Revenues are from selling electricity to grid and salvage values that occur at the end of the project lifetime. Despite the net present value (NPV), NPC considers costs as positive values and the revenues negative. Thus, the NPV and NPC are the same absolute value but differ in signs. Based on the HOMER assumption, the prices increase with the same rate in the project lifetime. Therefore, HOMER calculates the real discount rate, which is roughly equal to the nominal interest rate minus the inflation rate. HOMER does not apply fluctuations in currency value. It means that USD value is considered constant throughout the project lifetime. For each component of the system, the capital cost is specified by the algorithm in the initial year. The operation and maintenance cost is applied annually. The replacement cost of the components should not necessarily be the same as the capital cost as these two costs are affected by different parameters. For instance, WT nacelle may be required to be changed after 15 years.

Nevertheless, the tower would be in operation throughout the project life. In this example, the project’s replacement cost
is less than the capital cost. Yet, in another instance, consider a donor agency fund the project to some extent; however, they might not cover the replacement cost. Hence, in this case, the replacement cost is considerably higher.

To calculate the annual cost of each component, HOMER applies capital, maintenance, replacement, and fuel costs as well as the grid revenues. This hypothetical cost is attributed to one component of the system. To reach the annual cost of the system, HOMER sums up the other components cost as well as miscellaneous costs, such as environmental penalties imposed by the government. Using the following Equations (1) and (2), HOMER calculates the NPC:

$$C_{NPC} = \frac{C_{ann, tot}}{CRF(i, R_{proj})}$$  

(1)

where $C_{ann, tot}$ accounts for the annual cost of the system, $i$ is the real discount rate, $R_{proj}$ is the duration of the project, and $CRF(i, N)$ is the capital recovery factor:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}$$  

(2)

where $i$ accounts for the real discount rate and $N$ is for the number of years.

In order to calculate the COE, HOMER employs the following Equation (3):

$$COE = \frac{C_{ann, tot}}{E_p + E_d + E_{g,s}}$$  

(3)

As mentioned above, $C_{ann, tot}$ corresponds to the annual cost. The annual primary load and deferrable load are represented as $E_p$ and $E_d$, respectively. $E_{g,s}$ is also the annual sold energy to the grid. In Equation (3), the denominator represents the total yearly useful energy produced by the system. Furthermore, the COE is the average cost per kWh of useful energy produced by the system.

Operating cost is defined in HOMER as the annualized value of all costs as well as revenues despite initial capital costs, as Equation (4):

$$C_{operating} = C_{ann, tot} - C_{ann, cap}$$  

(4)

where $C_{ann, cap}$ is total annualized capital cost and is achieved by multiplying capital recovery factor by total initial capital cost.

In order to make a comparison between different systems, it is common to employ the COE. However, HOMER uses the NPC as its primary economic criterion in the optimization process. Therefore, HOMER optimally lists the system configurations based on minimum NPC. In this study, thermal energy is neglected. Also, grid sales are included as a means of energy production.

The fraction of the annual total energy production of the system that is generated from RESs is called renewable fraction (RF). When RF is equal to 100%, it means that the entire energy generation is from RESs. On the other hand, when RF is equal to 0%, it is concluded that the energy is generated from nonrenewable energy sources. The RF is also calculated using the following equation:

$$RF = \frac{E_{ren} + T_{ren}}{E_{pro}}$$  

(5)

where $E_{ren}$, $T_{ren}$, and $E_{pro}$ are the annual electricity generation from RESs (kWh/y), the annual thermal energy generation from RESs (kWh/y), and the annual total energy production (kWh/y), respectively. In our study, no thermal production or demand is considered.

### 2.2 Input data

For starting the simulations, the software needs input data including weather data, costs of components, load data, economic data (inflation rate, interest rate), and electricity buy/sell price data, which are mentioned in further subsections.

### 2.3 System control

Two dispatch strategies are available in HOMER simulation, namely, load following and cycle charging. Through the cycle charging strategy, the load is met the RES power generations at first. Then, the extra generated power is used to charge the BES. However, by load following, the BES is only charged by the RESs. In this research, a cycle charging strategy is adopted, and the simulation time step is 60 minutes.

### 2.4 System constraints

In this study, operation reserve and annual capacity shortage fraction are considered as the two systems constraints. The selected cities are assumed to be a reliable power system. However, for the grid-connected systems, the maximum capacity shortage was identified 1% per year. The reserve power requires 10% of the total load to support the load even when the RES generation drops down to 10%. However, because of the intrinsic inconsistency in the output of any RESs, a higher operation reserve is suggested. For the PV and WT outputs, the amounts are around 80% and 50%, respectively.
Iran is a vast country by covering 1.65 million square kilometers and enjoys a wide variety of climate conditions in different regions. The northwestern of Iran comprises a mountainous, cold climate with considerable precipitation during a year. However, in hot seasons the temperature is usually mild. The central and eastern parts of the country are mostly dry and hot. Two of the major deserts of Iran, namely “Kavir’e Lout” and “Dasht’e Kavir,” are included in these parts of the country. The northern part of Iran, along the shore of the Caspian Sea, comprises an entirely different climate by being mild and humid.

In the study of, Iran is divided into eight zones based on climate similarities. The major climate zones are as follows: very cold, cold, moderate and rainy, semimoderate and rainy, semiarid, hot and dry, hot and humid, very hot and dry. Ten cities are selected as representatives for these zones. The selected
cities are Yazd, Golestan, Gilan, Hamedan, Ahvaz, Bandar Abbas, Urmia, Bam, Tehran, and Lighvan. Additionally, this paper considered Tehran and Urmia as the supplementary cities, because this study aims to investigate the capital and Lake Urmia conditions deliberately. The geographical locations of these cities are represented in Figure 2. In this figure, the selected cities are illustrated as the bold red circles on the GHI map of Iran. NASA Surface Meteorology and Solar Energy database is used for weather data extraction (temperature, solar irradiance, wind speed). Table 1 shows yearly weather data for the selected cities. However, more details are available in, such as monthly weather data, which have not been mentioned in Table 1.

2.6 Economic parameters

According to, the average inflation rate and the discount rate over the last 5-year period in Iran are considered as 16.18% and 18%, respectively. Moreover, custom duties and VAT of all equipment have been assumed to be 25%-30%, according to the Islamic Republic of Iran Customs Administration (IRICA).

2.7 System configuration

The PV/WT/BES HMG considered for this study is exhibited in a schematic layout in Figure 3. Components of the system are PV, WT, an AC/DC bidirectional converter, charge controller, BES, AC and DC buses, and electrical load. BESs are designated to store extra generated electricity and use it when it is required by the system. The BES is integrated into the DC bus via a battery charge controller. The BES is a backup energy source and does not inject electricity into the grid. The bidirectional converter is employed for converting both AC and DC sources. According to the cycle charging strategy, the electrical load is mainly provided by the PV and WT systems.

2.7.1 PV system

Environmental conditions such as irradiation and temperature have significant effects on the PV system output. The output power of the PV system is calculated according to Equation (6):

$$P_{PV} = P_{PV - rated} \frac{I_T}{I_S} \left[1 + K_c (T_c - T_{ref})\right]$$

In (6), PV system rated power under standard test conditions is defined by $P_{PV - rated}$. The $f_{PV}$, $I_T$, $I_S$, $K_c$, $T_c$, and $T_{ref}$ denote the PV array derating factor, the global solar irradiation incident on the unit of the PV array surface, the solar irradiation to the unit of the PV array surface at standard temperature condition (25°C) ($I_S = 1 \text{ kW/m}^2$), the PV array temperature coefficient, the temperature of the PV cell and the temperature of the PV cell under standard test conditions, respectively.

In this study, Trina Solar (TSM-320PD14) 320 W solar panel was chosen due to its high efficiency and low cost.

2.7.2 WT system

Feng Teng (FT-1000M5) 1 kW WT is utilized in this research. HOMER can calculate the WT maximum output power at a particular hub height by referring to that turbine power curve.

| City         | Annual average of solar GHI resource (kWh/m²/d) | Annual average of ambient temperature (°C) | Annual average of wind resource (m/s) | Climate        |
|--------------|-----------------------------------------------|------------------------------------------|-------------------------------------|----------------|
| Yazd         | 5.40                                          | 15.87                                    | 6.56                                | Semiarid       |
| Golestan     | 4.25                                          | 16.98                                    | 4.71                                | Semimoderate and rainy |
| Gilan        | 4.25                                          | 15.75                                    | 4.84                                | Moderate and rainy |
| Hamedan      | 5.04                                          | 12.59                                    | 5.66                                | Cold           |
| Ahvaz        | 5.27                                          | 25.12                                    | 4.99                                | Very hot and dry |
| Bandar Abbas | 5.40                                          | 25.58                                    | 5.53                                | Very hot and humid |
| Urmia        | 4.87                                          | 9.81                                     | 5.95                                | Moderate and rainy |
| Bam          | 5.42                                          | 20.87                                    | 6.38                                | Hot and dry    |
| Lighvan      | 5.58                                          | 25.38                                    | 4.20                                | Very cold      |
| Tehran       | 4.89                                          | 12.63                                    | 5.79                                | Semiarid       |
and extract required data based on the wind speed, temperature and pressure data. In Figure 4, the wind speed at the height of the hub is plotted against the output power. It is noteworthy that if the wind speed is out of the range of the power curve, the WT produces no power either; it is below the minimum or above the maximum of the working limit of the turbine.8,51

2.7.3 | Converter

The conversion of AC to DC and vice versa is an integrated part of the system. This conversion is facilitated by the inverter and rectifier. The inverter should be designed in a way that withstands the maximum expected AC load. According to the Equation (6), the efficiency of the inverter is defined as the ratio of the input (AC power) to the output (generated DC power) from the BES or the PV system.52

\[
\eta_{\text{inv}} = \frac{P_{\text{inv, out}}}{P_{\text{inv, in}}}
\]  

where \( P_{\text{inv, out}} \) and \( P_{\text{inv, in}} \) represent the output and input power of the inverter, respectively. In this study, a bidirectional converter Sacolar (model: Sunicorn MHP) with 1 kW capacity is used for simulation53

2.7.4 | Battery storage system

For storing the surplus energy in the system, a rechargeable battery model is used. Therefore, a commercial 12 V/12 Ah lithium-ion battery is used for simulation.54

The charge controller is used for regulating the energy flow from the PV system to the BES. Charge controllers manage the charging/discharging cycles of the BESs. They are typically employed to protect the BESs against overcharge or overdischarge. This would enhance the reliability and longevity of BESs. Charging and discharging of the BES are preformed via the DC voltage charge controller.55

The specifications of utilized equipment are reported in Table 2.
2.8 | Grid

The maximum annual capacity shortage is considered around 1%. The guaranteed electricity purchase tariff (FiT) for PV and WT systems with a capacity of 10 MW is 4900 IRRs/kWh (0.12 $/kWh).56

2.8.1 | Grid purchased price (multi-period TOU)

In Iran, conventional electricity meters with fixed tariffs are being replaced with TOU electricity meters. TOU electricity meters calculate the price at three different rates during the day. Based on the electricity rates, the price is the highest at peak hours. On the other hand, the price gets lower at mid-peak hours, and during the night, both price and demand stay at their lowest point. TOU electricity meters report three different rates corresponding to the time of day. The price of electricity at peak hours is four times as much as the mid-peak periods, and at off-peak hours is one-quarter of mid-peak times electricity price. However, due to different weather conditions in Iran, the MOE of Iran established different electricity tariffs for each weather condition. In these tariffs, depending on weather conditions, cities or provinces could be included in one of four electricity price zones defined for tropical regions (TRs), and if the city or province does not include in TRs, it assumes as a nontropical region (NTRs). In warm months of TRs, the price of electricity is much less in comparison with NTRs because, in TRs, a considerable amount of energy is spent on air cooling. However, tropical months are limited, and they do not include all months of the year. General electricity

| Equipment | Electrical parameter | Value | Economic parameter | Value |
|-----------|----------------------|-------|-------------------|-------|
| WT        | Maximum power        | 1050 W| Quantity          | 1 qty |
|           | Rated wind speed     | 12.5 m/s| Capital cost ($)| 725  |
|           | Start-up wind speed  | 2.5 m/s| Replacement cost ($)| 725  |
|           | Rated voltage        | 24/48 V| O&M cost ($/y)  | 70   |
| PV        | Maximum power        | 320 W| Capacity (kW)     | 0.320 |
|           | Efficiency           | 16.5%| Capital cost ($)  | 116  |
|           | Operating temperature| 47°C | Replacement cost ($) | 116  |
|           | Temperature coefficient| −0.5| O&M cost ($/y)  | 10   |
|           | Lifetime             | 25 y|                 |      |
| Converter | Output power         | 1 kW| Quantity          | 1 qty |
|           | Output voltage       | 230 V| Capital cost ($)  | 155  |
|           | Efficiency           | 95% | Replacement cost ($) | 155  |
|           | Lifetime             | 15 y| O&M cost ($/y)  | 0    |
| BES       | Nominal voltage      | 12 V| Quantity          | 1 qty |
|           | Quantity             | 20  | Capital cost ($)  | 377.48 |
|           | Nominal capacity     | 1 kW| Replacement cost ($) | 377.48 |
|           | Initial state of charge| 100%| O&M cost ($/y)  | 10   |
|           | Minimum state of charge| 20% |                 |      |
|           | Lifetime             | 10 y|                 |      |

| $C_{TR}$ ($/kWh) | $C_{TR}^{3}$ ($/kWh) | $C_{TR}^{2}$ ($/kWh) | $C_{TR}^{1}$ ($/kWh) | $C_{NTR}$ ($/kWh) | $C_{NW-TR}$ ($/kWh) |
|------------------|----------------------|----------------------|----------------------|------------------|---------------------|
| 0.00962          | 0.01                 | 0.0088               | 0.004                | 0.012            | 0.012               |

TABLE 3 | Electricity tariffs for TRs and NTRs (mid-peak times)
prices for NTRs are separating into two main categories: the first 6 months of the year and the second 6 months of the year. In these two categories, periods of peak hours are different.\cite{57,58} During the first 6 months of the year, mid-peak hours are from 7 to 12 and 17 to 20. Moreover, there are two separate peak intervals as daily peak times and night peak times. The daily and night peak hours are from 12 to 17 and from 20 and 24, respectively. Also, the off-peak hours are from 24 to 7. In the second half of the year, the pattern of peak hours changes and just one peak interval exists, which is between 17 and 21.\cite{59,60} For the implementation of simulations, all electricity tariffs defined by MOE of Iran are considered. More information about the tariffs is presented in Tables 3 and 4.

In Table 3, different mid-peak electricity prices for all TRs and NTRs are presented. Electricity prices for mid-peak times in the first TR ($C_{TR1}$) and the second TR ($C_{TR2}$) are less than the other regions due to the high temperature and consumption of air-cooling systems. Table 4 is constructed based on Table 3. Table 4 presents different TR categories for each city.
for understudy cities. Furthermore, the tropical months, price in tropical months, and price in nontropical months for each understudy city have been presented.

A summary of the proposed strategy for the grid purchased price is illustrated in Figure 5. Based on this strategy, for each city, electricity prices are extracted from the tariffs defined by MOE of Iran. Then, the pricing regime, based on the city category, is considered for the optimal configuration of the energy system. As a result, if the city does not belong to TRs, electricity prices of NTRs are applied for optimization according to the description given above. Nevertheless, if the city belongs to any of TRs, electricity prices indicated in Table 4 are used for solving the optimization problem.
2.9 | Electrical load profiles

Hourly electrical load data of residential houses for 1 year are collected with personal attendance to the electricity distribution company. Figure 6 demonstrates monthly load profiles of ten residential loads in eight different climates. It is shown that in agreement with the weather conditions, the consumption patterns are differing from one another.

2.10 | Threats to validity

Although the simulations of this study have been done with great care, there still exist some inherent threats to validity. In this study, a continuous-stable process was developed through the research. All the simulations were conducted in HOMER software via high-end PC (32 GB RAM, CPU Core i7). Generally, to increase the validity and overcome intrinsic biases in different stages of the research, reliable secondary databases such as HOMER and NASA Surface Meteorology and Solar Energy were used. Reliable principles and framework were also used to establish a valid methodology. Moreover, in order to ensure the validity of the simulation results, two sensitivity analyses have been conducted on the system parameters, such as FiT and PV module price. Based on the results, NPC and COE changing trends are reasonably consistent with previous studies in the literature.27 However, uncertainties in weather and load data may affect the simulation results of the study, which have not been considered in this study due to limitations of HOMER software.

3 | RESULTS AND DISCUSSION

3.1 | Simulation results

The optimization algorithm of HOMER considers the weather potentials of each city as well as the cost of the components to obtain the minimum NPC. The optimal system configuration of each city is illustrated in Table 5. Based on the simulation results in Table 5, the use of RESs reduces NPC and COE in the mentioned climates of Iran. As an example, the city of Urmia as a semimoderate and rainy climate has the lowest NPC (~5839 $) and COE (~0.0122 $). The HMG in Urmia includes 4.81 kW and 9 kW of PV and WT systems, respectively. This is due to the climatic conditions of Urmia, as illustrated in Figure 1 and Table 1. It is revealed by the results of Table 5 that the climatic conditions of each city directly affect the system configuration. In addition to the climatic parameters in different regions of Iran (eg, wind speed, temperature, and solar irradiation), basic factors such as the size of PV, converter, and WT systems must be taken into account to supply electricity demand and so sell the electricity to the grid. According to the simulation results, using WTs in five cities of Golestan (semimoderate and rainy), Ahvaz (very hot and dry), Tehran (semiarid), Hamedan (cold), and Hormozgan (very hot and humid) is not cost-effective. This is due to the low wind potentials in these cities. However, the PV system is suggested for all climate zones because Iran has abundant solar potentials in all the considered climates. It is noteworthy that Urmia has the lowest operating cost among the other cities. In other words, annual revenues are much more than the capital cost of the system in Urmia and other cities with a negative operating cost.

One of the issues related to cities with lower NPC and COE is the high initial cost of the system, which is mainly due to the capital cost of the equipment. The large amount of RESs would subsequently result in higher capital cost of the system. This is following the results that exhibiting the highest initial cost for building HMGs in Urmia and Lighvan (very cold). It is mainly because of the high PV and WT power capacities. Nevertheless, the southern cities of Iran have lower initial costs (eg, Ahvaz (very hot and dry) has the least initial cost to build HMG). Furthermore, Gilan (moderate and rainy) has been optimized for the lowest PV and the highest WT power capacities.

According to the results of RF indicated in Table 5, the cities of Urmia (96.7%) and Yazd (semiarid) (96.6%) have the highest RF percentages. In comparison, Golestan (semimoderate and rainy) (56%) and Bandar Abbas have the lowest RF percentages. The high percentage of RF implies that the HMG is supplying electrical load by RESs in most hours. In other words, the electricity provided by the grid is much less than the electricity supplied by RESs. The city of Golestan, which has the lower RF (56%), should pay much more money to buy electricity in comparison with Urmia with the highest RF (96.7%). Urmia and similar cities with high RF sell much surplus electricity to the grid in comparison with those cities with lower RF. Based on the individual weather resources of each city and other mentioned inputs, the optimization algorithm tries to minimize the NPC of the system. The cost of electricity purchases from the grid is one of the most important costs that the algorithm tries to minimize it subject to other constraints. On the other hand, the algorithm maximizes the electricity selling to the grid. Therefore, the defined electricity prices in different cities can affect NPC and COE.

Figure 7 illustrates the optimal NPC and COE of each simulated system that is derived from Table 6. As can be seen in this figure, Golestan has the highest COE (0.012 $/kWh) and NPC (4520 $) among the other cities, while Urmia has the lowest COE (0.012 $/kWh) and NPC (4520 $). Tehran, which is the capital of the country, has the highest COE and NPC after Golestan. Six cities out of ten cities have positive values for COE and NPC, while the other four cities have negative values. This result shows the profitability of the project. It is concluded that weather parameters such as wind
speed, solar irradiance, and ambient temperature have a more significant effect on the optimum system configuration than just the climate zones. For instance, both cities of Urmia and Gilan are included in semimoderate and rainy climate conditions. However, by looking at weather resources in Table 1, it can be seen that the potentials of wind speed and solar irradiance of Urmia are more than Gilan, which will directly affect the optimal design of HMG and, consequently, financial results. Electricity prices defined by the MOE of Iran have also applied in simulations. Ahvaz and Bandar Abbas are the two cities that benefit from the lower electricity price in comparison with other cities. Both of these cities are included in TR 1.

Figure 8 shows the purchased and sold energy in all regions. Bandar Abbas (very hot and humid), Golestan (semimoderate and rainy), Tehran, Yazd, and Ahvaz (very hot and dry) were with the highest purchases of electricity in general. In contrast, cities such as Urmia and Lighvan have purchased less electricity in summer and had the highest sold electricity to the grid. In addition, Urmia and Lighvan sell less electricity to the grid in winter and instead buy more electricity from the grid due to their climate conditions. For example, in July, Urmia and Lighvan buy the least electricity from the grid and sell the most electricity. For the TRs of Iran such as Bam (hot and dry), Yazd, Bandar Abbas (very hot and humid), and Ahvaz (very hot and dry), electricity sold to the grid is higher in winter and lower in summer. These cities also buy more electricity in the summer.

Two cities of Lighvan and Urmia have almost an identical pattern for buying and selling electricity. In a similar case, Ahvaz and Bam follow an identical trend. Nevertheless, Bam purchases less electricity due to its higher RES productions. In Gilan, the purchased electricity has been decreased in warm months of the year. However, an abrupt increase has

### Table 5: Results of the optimum hybrid system for each city

| City     | PV (kW) | WT (kWh/qty) | BES (qty) | Converter (kW) | COE ($/kWh) | NPC ($) | Operating cost ($/y) | Initial cost ($) | RF (%) | Climate             |
|----------|---------|--------------|-----------|----------------|-------------|---------|---------------------|-----------------|--------|---------------------|
| Yazd     | 4.38    | 9            | -         | 4              | -0.00936    | -4784   | -700.85             | 9621            | 96.6   | Semiarid            |
| Golestan | 9.47    | -            | -         | 4              | 0.012       | 4520    | -20.54              | 5370.596        | 56     | Semimoderate and rainy |
| Gilan    | 2.52    | 10           | -         | 4              | 0.00143     | 726.67  | -435.19             | 4942            | 94.9   | Moderate and rainy   |
| Hamedan  | 9.35    | -            | -         | 4              | 0.00327     | 1272    | -172.43             | 4899            | 60.7   | Cold                |
| Ahvaz    | 10      | -            | -         | 4              | -0.00235    | -892.53 | -496.18             | 5135            | 62.2   | Very hot and dry    |
| Bandar Abbas | 9.49 | -            | -         | 4              | 0.0055      | 2322    | -127.77             | 4948            | 56.2   | Very hot and humid  |
| Urmia    | 4.81    | 9            | -         | 4              | -0.0122     | -5839   | -759.8              | 9778            | 96.7   | Moderate and rainy   |
| Bam      | 4.9     | 9            | -         | 4              | 0.000415    | 206.75  | -431.92             | 9085            | 93.5   | Hot and dry         |
| Tehran   | 9.23    | -            | -         | 4              | 0.00799     | 3220    | -79.56              | 4855            | 57.4   | Semiarid            |
| Lighvan  | 4.81    | 9            | -         | 4              | -0.00968    | -4676   | -703.17             | 9777            | 95.8   | Very cold           |

### Figure 7: Results of NPC and COE for different cities
TABLE 6  HMG Configurations with BES

| City    | PV (kW) | WT (qty) | BES (qty) | COE ($/kWh) | NPC ($) |
|---------|---------|----------|-----------|-------------|---------|
| Urmia   | 4.81    | 9        | 2         | −0.0112     | −5353   |
| Bam     | 9.6     | -        | 2         | 0.0028      | 1143    |
| Bandar Abbas | 9.52   | -        | 2         | 0.0066      | 2809    |
| Gilan   | 1.63    | 9        | 4         | 0.0079      | 3766    |
| Golestan| 9.36    | 1        | 2         | 0.0161      | 6138    |
| Hamedan | 9.34    | -        | 2         | 0.0055      | 2170    |
| Lighvan | 4.81    | 9        | 2         | −0.0086     | −4190   |
| Ahvaz   | 10      | -        | 2         | −0.0131     | −4577   |
| Tehran  | 8.22    | -        | 2         | 0.0092      | 3706    |
| Yazd    | 4.42    | 9        | 2         | −0.0084     | −4344   |

been in July, which led to reductions in electricity sell to the grid. In Hamedan city, the purchased electricity is decreased from April to June.

In contrast, the sold electricity to the grid is increased in these months. Furthermore, no significant changes have been seen in other months of the year. Golestan also has similar purchasing and selling patterns to Hamedan; however, as can be seen in Figure 8F, more variation is available in the patterns related to Hamedan’s electricity purchased and sold to the grid. Bandar Abbas is fairly different from the other cities. As can be seen in Figure 8C, the purchased electricity is slightly increasing from January to September, and on the other side, the sold electricity is simultaneously decreasing. Nevertheless, the purchased electricity is decreased from September to January and the electricity sold is moderately increasing between this period.

Figure 9 shows annual purchased/sold electricity from/to grid for each understudy city. As expected, Urmia has sold more electricity than the other cities. It has purchased the least electricity from the grid among other cities. On the other side, Bandar Abbas has purchased electricity more than the other cities, and it has sold relatively less amount of electricity compared to other cities. However, Golestan has the minimum value for the sold electricity to the grid.

In spite of several technical and economic merits of RESs such as PV and WT systems, there are environmental concerns regarding these resources that should not be neglected. PV cells usually contain toxic chemicals of cadmium and lead.61 In addition, several hazardous materials such as sulfuric acid, nitric acid, hydrogen fluoride are used for cleaning and purifying the surface of the cells. These materials are similar to ones which are used in semiconductors and would be a serious threat to environmental and public health if they are not disposed of properly. Since the Iranian government did not consider any particular policy for collecting PV disposal, the mentioned threats are more significant. Hence, MOE of Iran, in cooperation with the other organizations, should put forward actions and policies for collecting disposal of PV modules to alleviate concerns and threats to people and the environment.

The other environmental concern is related to WT systems. Proliferations of RESs such as WT system that has raised the risk of bird’s mortality. Reports indicated that different species of birds such as kestrels and vultures have collided with blades of WT thereupon, they were killed. MOE of Iran should prevent occurring such environmental damages by protecting birds from poorly sited WT development.

3.2   BES feasibility

As it is evident, in none of the optimal configurations, BES has participated. So, the results claim that since MOE of Iran has not considered any policy for selling electricity from BES to the grid, the stored energy in BES could be just used for load requirements, especially in the peak times. However, it does not provide economic to use BES in the system configuration. Moreover, the lifetime and replacement cost are important parameters in removing of BES in the optimal system. If the MOE of Iran legislates on buying stored electricity in BES from customers, then the optimal system would be considered differently. As a suggestion in this paper, the assumption that the MOE purchases battery power is put forward, and the simulation results are repeated. It is assumed that MOE buys the battery-stored electricity as with a guaranteed purchased price (0.012 $). It was observed that due to the high initial cost of the BES and considering the optimal battery life, using batteries are still not economically efficient. According to this plan, if the grid purchases the battery electricity, the configuration of the PV/BES/WT system would be obtained for Urmia, which is slightly different from the optimum configuration. System configurations and economic results for all cities are shown in Table 6.

Based on the details indicated in Table 6, the existence of BES in the system configuration has increased the NPC and COE of all the cities. However, the best city with the lowest NPC and COE is still Urmia with −5353 $ and 0.0028 $/kWh for NPC and COE, respectively. Similar to the previous case, which no plan was assumed for buying electricity from the BES, Golestan has the worst economic results based on the values of NPC (6138 $) and COE (0.0161 $/kWh). Furthermore, Gilan has the most contribution of BES in its system configuration by 4 quantities. Tehran has the least capacity of RESs by 8.22 kW of PV system, and Urmia benefits from the highest capacity of RESs by 4.81 kW for the PV system and 9 quantities for the WT system.

Despite the technical benefits of batteries in HMG structure, such as storing extra generations of RESs and consuming it in emergency conditions, there are environmental concerns about battery integrations in MG structure. As a matter of
FIGURE 8  Purchased/sold electricity from/to the grid in different cities
fact, some batteries, such as nickel-cadmium and lead-acid batteries, are toxic and create environmental threats. Disposal of different types of batteries has to be handled properly. Therefore, a clear strategy is needed to be considered by the MOE of Iran for safe collecting of batteries disposal to prevent environmental hazards.

3.3 | Sensitivity analysis

Two sensitivity analyses have been performed in this section as follows:

- Sensitivity analysis 1: The sensitivity analysis is performed to investigate the impacts of increases in the price of electricity sales (known as FiT) on the economic results for all the understudy cities.
- Sensitivity analysis 2: The second sensitivity analysis investigates the impacts of different module prices on NPC and COE for all the cities.

3.3.1 | Sensitivity analysis 1

In this case, sensitivity analysis has been performed via the changes in FiT. MOE of Iran plans to increase FiT (sell back price) to encourage people to use more of RESs. Therefore, the impact of the increase in FiT on the COE and NPC is investigated.

Two possible values as 0.17 and 0.25 have been used for investigations. Figures 10 and 11 show the economic results of sensitivity analysis for the hybrid systems based on the increased values of FiT. Electricity purchased price was considered similar to the previously defined rates with no changes. Since there are several plans by MOE of Iran to raise the guaranteed electricity purchase price, the sellback price was increased to obtain the results. As expected, with soaring the FiT, the values of NPC and COE decrease. All understudy cities and their related climates are having a negative NPC and COE when FiT is gone up from 0.12 $ to 0.17 $. It can be concluded that if the MOE of Iran increases only 0.08 $ to the current FiT (0.12 $), almost all the cities would benefit economically from the contribution of RESs in their systems. It is observed that the cities of Urmia (moderate and rainy) and Yazd (semiarid) would have the most NPC and COE reduction rates when the FiT increases from 0.12 $ to 0.17 $. Additionally, simulation results for NPC and COE demonstrate that Golestan city has the smallest reduction among the other cities. Similar behavior is seen when the FiT is raised from 0.12 $ to 0.25 $. However, the system would be much more economical compared to the case with 0.17 $ for FiT. Urmia is still the top-ranked city by the lowest values for NPC and COE with −46 855 $ and −0.0925 $/kWh, respectively. Moreover, Golestan has the highest values of NPC (−18 037 $) and COE (−0.33 $/kWh). Based on the results, it
can be observed that FiT is one of the main decision factors, which would lead to economic HMG configuration if the authorities pursue the policies for increasing current FiT.

### 3.3.2 Sensitivity analysis 2

The second sensitivity analysis has been performed on the price of solar modules. As mentioned in previous sections, Iran has got great potential for exploiting PV systems. Also, simulation results have recommended the PV system as the main RES for the optimal configuration of HMGs in all cities. Previous simulations have shown that utilizing the PV system in HMG configuration would lead to reductions in NPC and COE.

In this sensitivity analysis, different capital and replacement costs for PV modules are considered, and their effects on the economics of the proposed system have been investigated. Results of sensitivity analysis on the solar panel capital and replacement costs are shown in Figure 12. A general overview of the results indicates that by increasing capital and replacement costs, COE and NPC increase simultaneously. However, the impact of the cost reduction rate is much more than the cost increment on the NPC and COE.
Figure 12: Results of sensitivity analysis on the solar panel capital and replacement costs.
Urmiya is the ideal city, which does not face with abrupt changes of NPC and COE by an increase in capital and investment costs from 29 $ to 203 $. It can be seen that the city still has negative NPC and COE when the capital and replacement costs are increased to 203 $. Yazd and Lighvan are also following a similar pattern as Urmiya. However, the slope of the increase in NPC and COE is more significant in these two cities in comparison with Urmiya. Gosalten and Tehran have got the worst economic results compared to other cities. Even if the capital and replacement costs of the PV system are reduced to 23 $, these cities have positive NPC and COE. Hamedan city is also pursuing a similar trend as Tehran, whereas Hamedan benefits from negative values of NPC and COE for 23 $ of capital and replacement costs. As can be seen from Figure 12A, decreasing the PV system capital and replacement costs do not significantly affect the NPC and COE of the system. Moreover, by increasing the price of PV module from 116 $ to 203 $, COE and NPC are zero, which shows the minor impacts of PV module prices on the NPC and COE of the system. Different results are shown in Figure 12B, which shows the significant effect of PV module price on the values of NPC and COE. As can be seen, any changes in module price would improve or deteriorate the economic results of the system. The best and the worst values of NPC and COE are achieved with 23 $ and 203 $ for PV module.

On the other hand, Bandar Abbas and Gilan are the two cities that do not follow the same pattern with Bam. In Bam, a direct and linear relationship has been seen between economic results and PV module prices. Nevertheless, in Bandar Abbas and Gilan, this relationship is not entirely linear. For instance, for the 145, 176 $ and 203 $ prices for PV module, NPC and COE values are almost constant. The same results are also visible for Ahvaz, as mentioned above. In summary, the PV module price is an important factor that has a considerable effect on NPC and COE. However, this effect is more significant in some cities such as Bam.

The comparison of the results of this study with the other studies conducted in different climates implies significant achievements.

In this study, it was shown that the combination of distributed energy sources would reduce NPC and COE of HMGs rather than using single PV or WT. Studies in 19,20 also reported similar results as PV-based, or DG-based systems result in higher NPC and COE compared to their discussed HMGs. As same as the previous study in Nigeria,21 it is shown that using WT in the hybrid system with a low potential of wind speed is not economically feasible. A recent study conducted in different climates of China27 stated that the grid-based system was the most economical. However, in contrast to this study, in our simulations in different climates of Iran, PV/WT and grid combination is the most economical system. This is because of current policies on electricity prices and the economic status of Iran. The economic infeasibility of BES in grid-connected HMGs has been shown in,6 which is consistent with our study. However, in the proposed configuration for HMGs such as,31 using the BES was found to be feasible. In,12 an off-grid HMG has been analyzed in three different climates of Iran. It has been concluded that Kish, with very hot and humid climate conditions, obtains the best economic results. However, in our study, grid-connected HMG in Urmiya with semimoderate and rainy climate conditions achieved the best economic results.

4 | CONCLUSIONS

In this study, HOMER software has been effectively utilized to investigate an introduced HMG, including the grid/PV/WT/converter, and BES. Moreover, ten cities were selected in eight different climate zones of Iran to investigate the techno-economic feasibility of the proposed HMG. According to the simulation results, the minimum NPC and COE obtained for Urmiya (COE = −0.0122 $/kWh, NPC = −5839 $), Lighvan (COE = −0.0097 $/kWh, NPC = −4676 $), and Yazd (COE = −0.0094 $/kWh, NPC = −4784 $), respectively. The combination of grid/PV/WT/converter was the most economical configuration, while the investment cost was reported as the highest. Furthermore, the lowest initial capital cost was obtained by the combination of the grid and PV system.

Moreover, it has been shown that using BES in the HMGs is not feasible at the current conditions of Iran. This is mainly because of the high capital cost and lack of any incentive program for buying power from BES. The increase in PV module prices resulted in higher NPC and COE for almost all the cities. Therefore, efforts must be made to control the price of the PV modules. The northwestern cities of Iran with a semimoderate and rainy climate conditions (eg, Urmiya and Lighvan) are the most suitable locations for building HMGs from both technical and economic points of view. In all the selected climate zones, COE and NPC of HMGs were decreased by the increase in RES power purchase price. Hence, in order to increase the local usage of RESs in the country, authorities must plan to increase FiT.

NOMENCLATURE

Parameters

| Symbol | Description |
|--------|-------------|
| \( C_{NPC} \) | Net present cost ($) |
| \( C_{ann.tot} \) | Annual cost ($/y) |
| \( i \) | Annual rate of interest (%) |

Annual rate of interest (%)
CRF \((i/N)\) Capital recovery factor

\(R_{\text{proj}}\) Duration of the project (y)

\(N\) Number of years

\(\text{COE}\) Levelized energy cost ($/kWh)

\(E_p\) Annual primary load (kWh/y)

\(E_d\) Deferrable load (kWh/y)

\(E_{g,s}\) Annual sold energy to the grid (kWh/y)

\(\text{COE}\) Operating cost ($/y)

\(C_{\text{ann, cap}}\) Total annualized capital cost ($/y)

\(R_{\text{proj}}\) Mid-peak electricity price for tropical region 1 ($/kWh)

\(C_{\text{TR}2}\) Mid-peak electricity price for tropical region 2 ($/kWh)

\(C_{\text{TR}3}\) Mid-peak electricity price for tropical region 3 ($/kWh)

\(C_{\text{TR}4}\) Mid-peak electricity price for tropical region 4 ($/kWh)

\(C_{\text{NTR}}\) Mid-peak electricity price for nontropical region ($/kWh)

\(C^{\text{NW-TR}}\) Mid-peak electricity price for nonwarm months of the tropical region ($/kWh)

\(\text{RF}\) Renewable fraction (%)

\(E_{\text{ren}}\) Annual electricity generation from renewable sources (kWh/y)

\(T_{\text{ren}}\) Annual thermal energy generation from renewable sources (kWh/y)

\(E_{\text{pro}}\) Annual total energy production (kWh/y)

\(P_{\text{PV}}\) PV system output (kWh)

\(P_{\text{PV-rated}}\) Rated power of the PV system under standard test conditions (kW)

\(f_{\text{PV}}\) PV derating factor in (%)

\(I_T\) Global solar irradiation incident on the unit of the PV array surface (kW/m²)

\(I_S\) Solar irradiation to the unit of PV array surface at standard temperature condition (25°C) (kW/m²)

\(K_C\) PV array temperature coefficient (%/°C)

\(T_c\) The temperature of the PV cell (°C)

\(T_{\text{ref}}\) The temperature of the PV cell under standard test conditions (°C)

\(\eta_{\text{inv}}\) Inverter's efficiency (%)\n
\(P_{\text{inv, out}}\) Inverter's output power (kW)

\(P_{\text{inv, in}}\) Inverter's input power (kW)

Abbreviations

HPS Hybrid power systems

HMG Hybrid microgrid

PV Photovoltaic

WT Wind turbine

DG Diesel generator

COE Levelized cost of energy

NPC Total net present cost

NPV Net present value

TOU Time of use

BES Battery energy storage

RES Renewable energy resource

RF Renewable fraction

TR Tropical region

GHI Global solar atlas

VAT Value-added tax

IRICA Islamic Republic of Iran Custom Administration

CONFLICT OF INTEREST

None declared.

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