

Chapter 9

Design of CCHP System with the Help of Combined Chiller System, Solar Energy, and Gas Microturbine



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Abstract This work was conducted to design a combined cooling, heating, and power (CCHP) system with photovoltaic energy which provides simultaneous generation of electricity, heat, and cold for a high-rise office building (23 floors) in the city of Mashhad in Iran. Our strategy was to supply load electric, thermal, and refrigeration with the help of solar energy. In addition, its superiority over other systems was evaluated. Analysis and study of solar radiation and the maximum level of solar panels use, according to the architectural plan, were carried out at the project site. The analysis of shadow points, the use of inverters and electrical detectors to increase the maximum solar power, and its cost-effectiveness were carefully studied via PVSOL software. Additionally, the amount of heat, cold, and electricity consumption was accurately calculated according to international standards and utilizing HAP software. The criteria for saving on the initial cost reduction, carbon dioxide emission reduction, operating cost reduction, payback period, revenue, and the minimum life expectancy of the equipment compared to those in other methods were also evaluated. The results obtained from the designed system of simultaneous generation of electricity, heat, and refrigeration, which combines gas microturbines as the primary stimulus, a combination of absorption and compression chiller to provide refrigeration load, a boiler for auxiliary heat load, and a thermal photovoltaic system to produce both electric and thermal loads, were finally revealed. This is believed to be a cost-effective strategy for high-rise residential or commercial buildings with a geographical location like that of Mashhad. Based on the electricity sales to the grid, with the rate of increase in inflation in electricity tariffs, this design in the Mashhad project was estimated to have an annual income of 166.676 thousand

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dollars. Moreover, the initial capital return period in this project was calculated to be 5.19 years.

Keyword CHP · CCHP · PV system · Building energy saving · T-EA

9.1 Introduction

The world's energy demand is increasing, and fossil fuel sources are declining.

Therefore, finding solutions to manage their consumption of particular importance, especially to reduce emissions. One of the best solutions is to use renewable sources (RESs), especially solar (Makkiabadi et al. 2021a, b) and wind energies (Kokkos et al. 2021). RES can provide an affordable and safe supply (Mago and Hueffed 2010). If the rate of extraction of an energy source does not exceed the natural rate of replenishment, it can be called as a sustainable energy source (Makkiabadi et. al 2021a, b; Razmjoo et al. 2021). Building sector consumes the highest amount of energy and electricity (Lamagna et al. 2020), especially to maintain their standards (Astiaso Garcia 2016). Building information modeling (BIM) is a digital tool used in different aspects, engineering design, construction, and management, understanding the sharing and transmission of building data in the whole life cycle of project planning, operation, and maintenance based on the integration of building data and information model (Agostinelli et al. 2022). Then, engineering and technical personnel can understand and take efficient response to various building information, providing the collaborative assistance model for all construction entities including design team, and construction and operating units (Peng et al. 2020). In addition, given the statistics, 85% of the Internet of Things (IoT) devices use digital twins' technologies for security monitoring, so applying the digital twins to the construction of smart cities has become the research hotspot in the field (Qin et al. 2021). Different parameters of buildings energy can be linked to the digital twin building section of the neighborhood for energy consumption monitoring, costs, and optimization (Manfren et al. 2021).

With the advent of technology, RES can be employed for electricity and heat generation in this sector (Nastasi 2019). Ahn (2019) examined the environmental and economic performances of an absorption chillers versus hybrid chillers in a CCHP system in a hospital. Those kinds of systems can offer stability (Konečná et al. 2020), controllability (Gu et al. 2012), electricity (Ehyaiei and Bahadori 2007), and heat generation (Ebrahimi and Keshavarz 2013). Researchers have studied simultaneous generation to reduce peak load using multi-objective planning and concluded that electricity prices, natural gas prices, and PV efficiencies have different effects on performance (Yang et al. 2021). Qian et al. (2021) proposed a novel combined model based on multi-objective decision-making to analyze the performance evaluation of the wind–solar–CCHP systems. The use of thermal photovoltaics by Lianga et al. (2015) in a residential building in China showed that 31.7% of the thermal energy of the building could be supplied with 132 m² of collectors. Moreover, the use of

solar energy in the facade of a building in one of the cities in Iran was investigated to provide at least 20% of the monthly electricity required for the critical month (Hoseinzadeh et al. 2021). The use of solar energy on the roofs of buildings in Valencia has also been analyzed to meet electricity demand (Gomez et al. 2021). Several researchers have also studied the combined PVT/water (Chow et al. 2007) and PVT/air systems (Kalogirou and Tripanagnostopoulos 2006). They have found that the natural flow of water is more efficient for receiving heat from the module and lowering the cell temperature. Jalalizadeh et al. (2021) simulated and studied a new combination of building solar heat collectors and absorption cooling system, as a three-dimensional production system, to meet the thermal and electrical energy needs of a residential building. The use of this proposed system has contributed to energy and economic savings and reduced the building energy consumption (De Santoli et al. 2018). CCHP is a powerful tool for increasing energy efficiency, and RES is ideal energy alternatives. Thus, the integration of them is a promising solution to remedy energy-related issues.

Compared with a conventional CCHP system, the hybrid CCHP system has better energy-saving and CO₂ reduction performance. However, the hybrid CCHP system consumes higher annual total cost on account of its high initial investment (Yang and Zhai 2018).

In this paper, the design, management, and evaluation of the CCHP system coupled with RES for a 23-storey office building in Mashhad (Iran) were carried out.

The CCHP system includes a gas microturbine, as primary actuator for power supply, in addition to an absorption and compression chillers for cooling and a boiler for heating. PV and solar thermal panels were used to supply electricity and hot water.

9.2 Weather

The collection of climatic information, such as the amount of sunlight and air temperature, is of particular importance in the design of RES (Manfren et al. 2020).

Figure 9.1 depicts the minimum, maximum, and average temperatures of Mashhad separately for each month.

In Fig. 9.2, the average dry temperature and the percentage of air humidity in Mashhad are shown separately for 24 h each month.

Figure 9.3 represents the average dry air temperature in Mashhad over one year at different times of the day for each month in the color spectrum.

In the diagram in Fig. 9.4, the amount of solar radiation is illustrated as a bar graph for each month.

Figure 9.5 shows the wind speed, temperature, and sundials of Mashhad in a period of one year as a flow chart.

The diagram in Fig. 9.6 describes the position of the sun in different months along with the temperature of Mashhad.

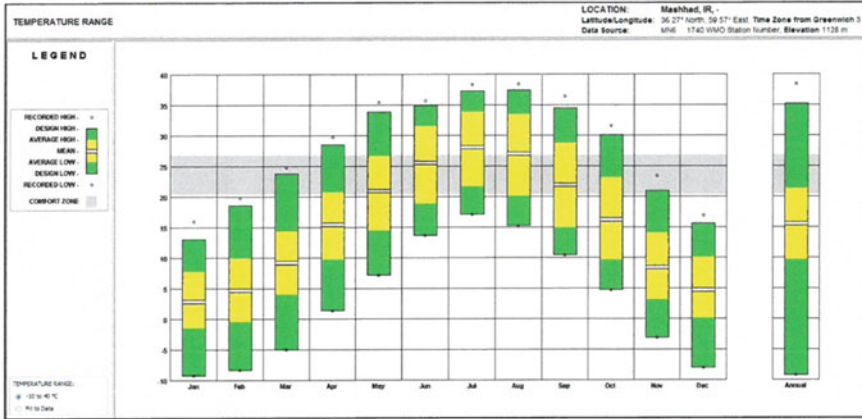


Fig. 9.1 Temperature graph of Mashhad in each month. Source PVSOL software

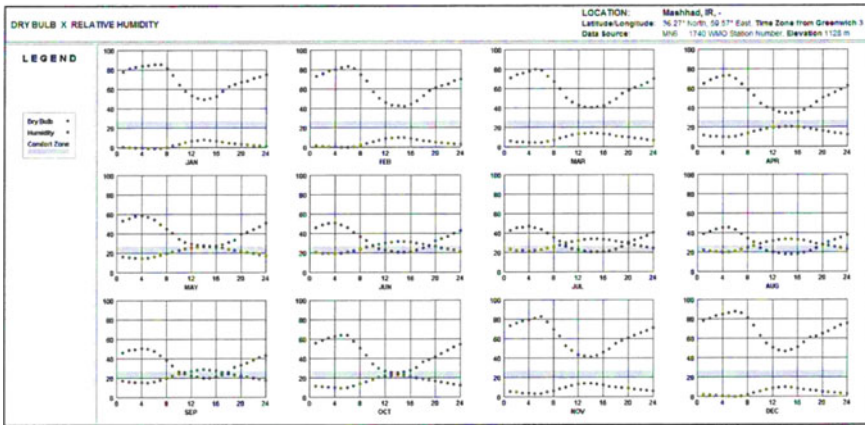


Fig. 9.2 Chart of dry temperature and humid temperature of Mashhad in one year. Source PVSOL software

9.3 Photovoltaic System

Since the project is inside the city and uses solar electricity to achieve maximum power and optimal use of radiation, the considered PV system is a grid-connected system. According to the architectural plans and consumption table, about 150 kW of solar panels with an efficiency of 14.7% was considered on the roof. PV panels were placed as follows.

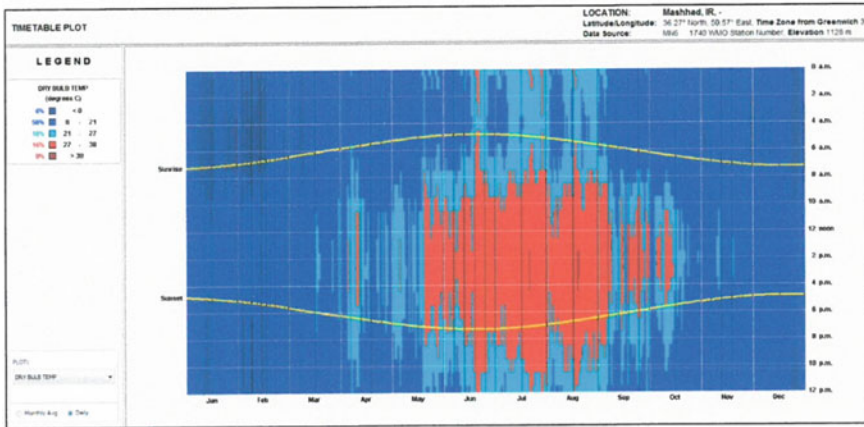


Fig. 9.3 Mashhad dry temperature diagram for one year. Source PVSOL software

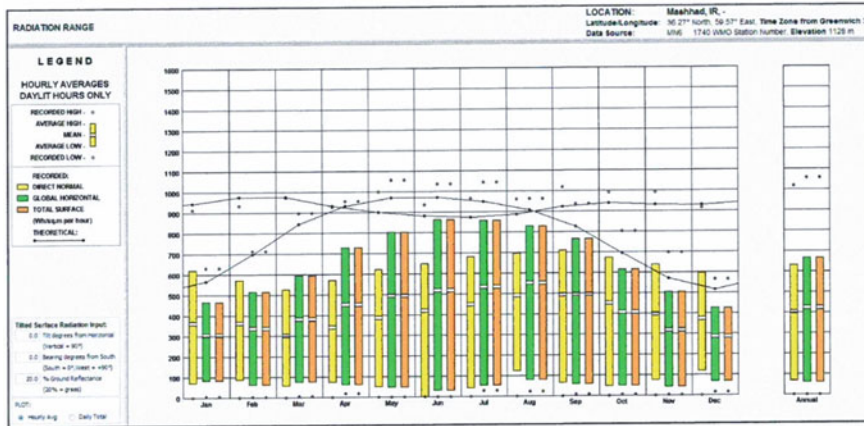


Fig. 9.4 Chart of solar radiation by month. Source PVSOL software

The presence of a shelter on the roof of the building (Fig. 9.7) necessitated examination and analysis of the shadows of this shelter on the solar panels. This analysis was performed with the software for one year. The results are shown as a color spectrum in Fig. 9.8. In this form, green spaces have very little shade and spaces that go red have the most shade in a year. In addition, spaces that do not cast shadows during the year are colorless. Figure 9.9 demonstrates how the PV panels were connected, which were then connected to the inverter.

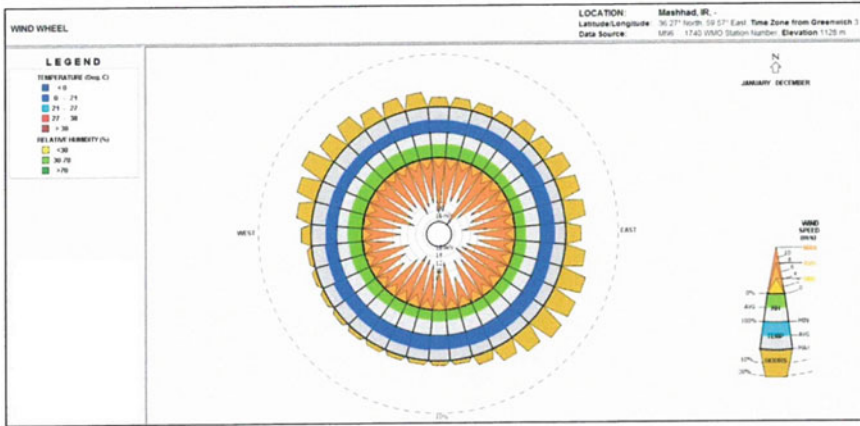


Fig. 9.5 Flower diagram of a year in Mashhad. Source PVSOL software

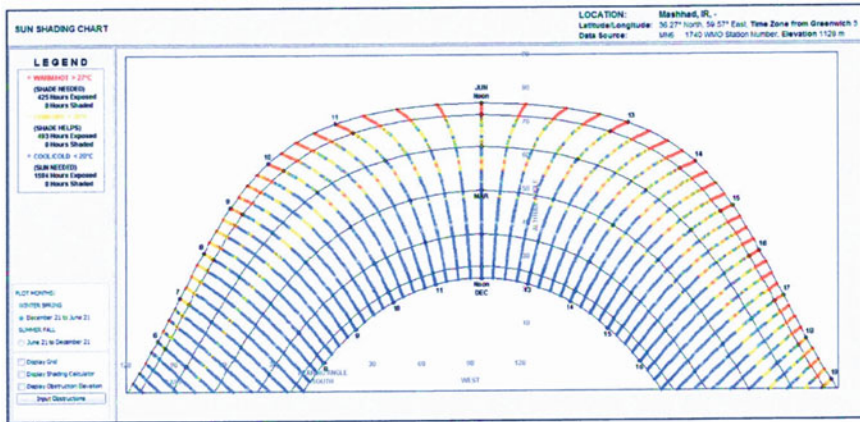


Fig. 9.6 Analysis of the position of the sun over a period of one year at the project site. Source PVSOL software

9.4 Energy Consumption

To calculate the heat and cooling load of the office building, HAP2 software was used. Thus, cooling, heating, and hot water loads were calculated according to Table 9.1.

The daily profile of the use of electrical equipment for this office building is based on the architectural plan and according to the reference Qian et al. (2021).

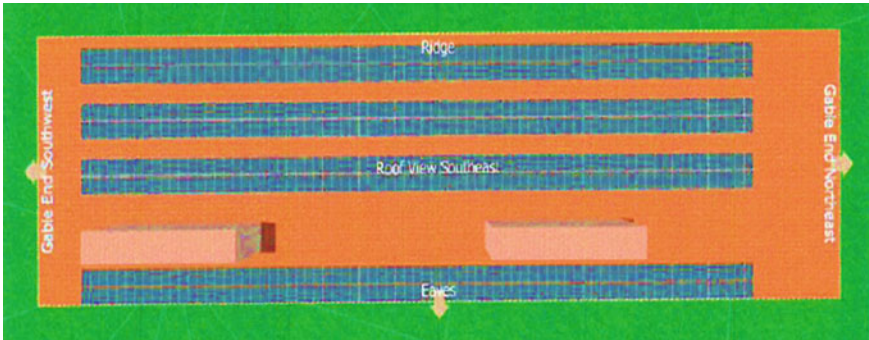


Fig. 9.7 How to place a photovoltaic panel on the roof of an office building. *Source* PVSOL software

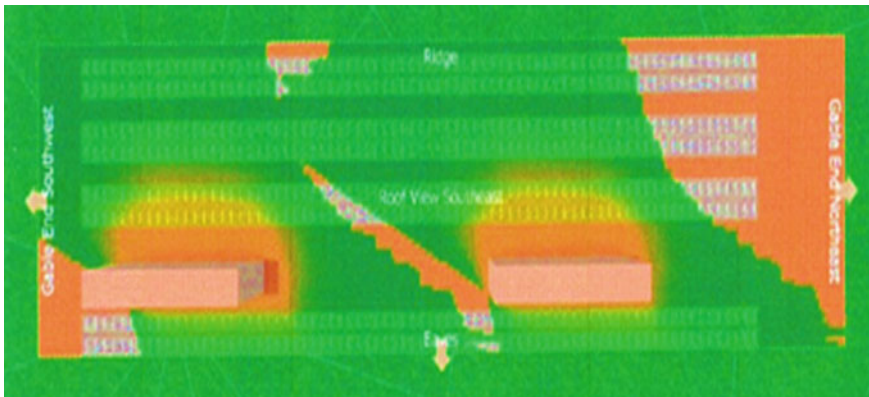


Fig. 9.8 Results of roof shadow analysis of office building. *Source* PVSOL software



Fig. 9.9 How to connect solar panels. *Source* PVSOL software

Table 9.1 Results of energy demand analysis in a high-rise office project

Number	High-rise office building loads	Annual energy demand (MWh/year)
1	Thermal load	2152
2	Cooling load	4254
3	Electrical load	4344
4	Heat load of hot water consumption	5019

9.5 Problem Definition

To obtain the energy demand estimation system in the mentioned office and to increase the reliability and stability of the system, a combination of PV system with a unique CCHP system was used in comparison with the separate production system, whose schematic is shown in Fig. 9.10. To determine the quality and superiority of the combination of CCHP and PV production systems, this case was compared to other scenarios in Table 9.2. The total project cost in dollars per year was obtained via Eq. (9.1).

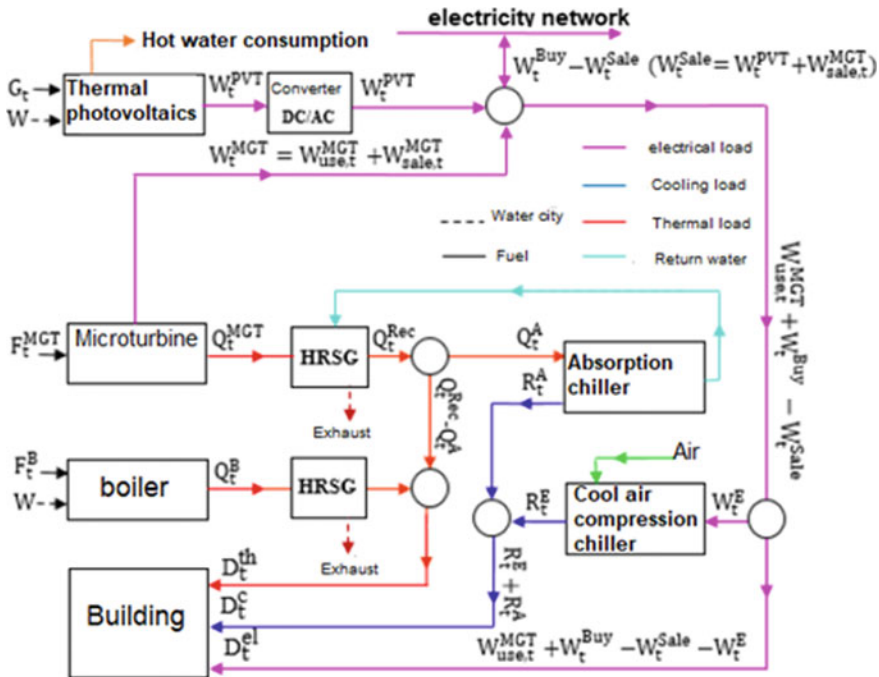


Fig. 9.10 Schematic of CCHP system with a PV system

Table 9.2 Scenarios studied

Scenario	1	2	3	4
PV/thermal			✓	✓
Gas microturbines				✓
Boiler	✓	✓	✓	✓
Cool air compression chiller	✓	✓	✓	✓
Absorption chiller			✓	✓

$$\text{Net cost} = C + C^F + C^M + C^G - B^G - B^Q \tag{9.1}$$

where C is the total initial cost of the purchase in dollars per year. C^F is the total gas consumption, boilers, and gas microturbines in dollars per year. C^G is the total cost of purchasing electricity from the grid in dollars per year. B^G is the revenue from electricity sales of gas microturbines and PV systems in dollars per year. B^Q is the revenue generated by the heat generation of gas microturbines and PV systems in dollars per year. In this case, it was assumed how much it will cost if the amount of heat produced by the gas microturbine or the amount of hot water produced by the PV collector for one year is provided by the boiler. This cost is the revenue generated for heating from gas microturbines and hot water from PV collectors.

9.6 Results

Table 9.3 shows the design results of combining a PV system with a CCHP system in comparison with other systems in four scenarios.

Considering Table 9.3, in Scenario 1, it was assumed that the building’s electricity demand is met by the electricity grid distribution, heated with a boiler, and the requested cooling is provided with a compression chiller. In this case, the project net cost is 21 k\$/y. This system did not have income and capital return because it was just a consumer. In Scenario 2, the capacity of the compression chiller was slightly reduced, and an absorption chiller was added to the system. The project net cost was reduced by 65%. Still, like in Scenario 1, the system did not have revenue and return on investment just because it was a consumer. In Scenario 3, the same combination of Scenario 2 plus gas microturbine was used. This resulted in a net project cost of 2.32 times higher than Scenario 2. The revenue from the sale of gas microturbines’ heat to the distribution network was estimated to be 108.43 k\$/y, and the revenue from the heat generation of gas microturbines (to reduce boiler consumption) was estimated to be 15.39 k\$/y. In total, the return on investment was calculated about 5.46 years. In Scenario 4, the use of the same devices as in Scenario 3 in combination with the PV system was considered. Therefore, with this combination of CCHP and PV, the project cost increased by 6.18%. However, the revenue from the sale of electricity to the distribution network was 166 k\$/y, which was about 54% more than

Table 9.3 Design results of combining PV system with CCHP and separate production system using different scenarios

Scenarios	1	2	3	4
Cap ^{PVT} (kw)	0	0	0	150
Cap ^{MGT} (kw)	0	0	2 * 260	2 * 260
Cap ^B (kw)	3 * 675	3 * 675	3 * 675	3 * 675
Cap ^A (kw)	0	281	281	281
Cap ^E (kw)	6 * 710	6 * 617	6 * 617	6 * 617
Net cost (k\$/year)	289.21	284.44	660.68	701.53
C (k\$/year)	138.75	132.11	268.74	371.42
C ^F (k\$/year)	18.99	18.99	361.05	361.05
C ^M (k\$/year)	42.75	41.24	86.42	86.62
C ^G (k\$/year)	88.72	92.09	68.28	68.28
B ^G (k\$/year)	0	0	108.43	166.67
B ^Q (k\$/year)	0	0	15.39	19.17
ROI (year)	0	0	5.46	5.19
B _{20 year} (k\$(0	0	28,679	43,197

that in Scenario 3. The revenue from heat generation from gas microturbines and PV systems also increased by 25% per year compared to Scenario 3. Furthermore, the income after 20 years was at least the lifespan of the equipment. Considering the inflation rate of 20.6%, it was estimated to be 43 k\$/y, which is 1.5 times more than in Scenario 3. Scenario 4, a PV thermal system was combined with a CCHP system, including gas microturbines, boilers, absorption chillers, and compression chillers.

The superiority of Scenario 4 was owing to the minimum return on investment and the highest income in the minimum life of equipment.

9.7 Conclusions

Integration of CCHP and RES makes a very strong strategy since it is conducive to the supply of clean energy for commercial and residential buildings. The CCHP technologies could provide methods for improving the utilization efficiency of RES energy. RES will provide a clean and cheap energy source.

The integration of CCHP system with RES energy can realize mutual compensation of two kinds of technologies. Governments have made very good policies to make further use of RES energy and CCHP production systems and to reduce fossil fuel consumption. Iran is no exception to this rule. The encouragement of the Ministry of Energy and the New Energy Organization of Iran (SABA) has been highly effective. Among them, the following could be mentioned:

- Guaranteed purchase, electricity generated by solar systems, and CCHP generation systems at a very reasonable price compared to the selling price.
- Fuel supply of production systems at the same time as the fuel supply rate of power plants for 20 years.

Hence, utilization of the proposed design in this article could be a promising, suitable, and economical option for investment, reducing energy consumption, and reducing environmental pollutants for the design of commercial, residential, and especially commercial buildings for regions with similar climatic conditions to Mashhad.

At first, wind speeds are predicted for future using a new combined intelligent model. For this purpose, three feedforward networks have been used. This type of wind speed prediction can be very efficient in the Iranian wind energy industry, and this research in this field is not similar in the world. The proposed model was evaluated with various network models, functions, and different numbers of neurons to extract optimal network structure. Furthermore, training and validation data were used to evaluate and compare diverse network structures' performance. The proposed model also was trained with training algorithms BFGS, LM, and BR. As the results show, with the right Perceptron neural network training methods, the HNN neural network can be trained better than a single neural network. Training a Perceptron neural network with an LM algorithm leads training error to reduce quickly since the LM algorithm is reasonably fast. Therefore, it is logical to select as the training algorithm of the first-level neural network in the hybrid model.

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