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Design, and optimization of COVID-19 hospital wards to produce Oxygen and electricity through solar PV panels with hydrogen storage systems by neural network-genetic algorithm

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A B S T R A C T

COVID-19 has affected energy consumption and production pattern in various sectors in both rural and urban areas. Consequently, energy demand has increased. Therefore, most health care centers report a shortage of energy, particularly during the summer seasons. Therefore, integrating renewable energies into hospitals is a promising method that can generate electricity demand reliably and emits less CO2. In this research paper, a hybrid renewable energy system (HRES) with hydrogen energy storage is simulated to cover the energy demand of sections and wards of a hospital that dealt with COVID-19 patients. Produced Oxygen from the hydrogen storage system is captured and stored in medical capsules to generate the oxygen demand for the patients. Results indicate that 29.64% of the annual consumed energy is utilized in COVID-19 sections. Afterward, modeled system has been optimized with a neural network-genetic algorithm to compute the optimum amount of the demand power from the grid, CO2 emission, oxygen capsules, and cost rate. Results determine that by having 976 PV panels, 179 kW fuel cell, and 171.2 kW electrolyzer, annual CO2 emission is 315.8 tons and 67,833 filled medical oxygen capsules can be achieved. The cost rate and demand electricity from the grid for the described system configuration are 469.07 MWh/year and 18,930 EUR/hr, respectively.

1. Introduction

Medical centers are accounted as the major consumer of electrical energy in the building sector [1]. One of the significant issues is to supply the energy demand of hospitals and health care centers [2]. Hospitals and health care centers are an energy-intensive category of buildings that are required to operate 24 h per day and 365 days per year [3]. Due to the competitive commercial environment, cost reduction in hospitals is one of the main concerns of hospitals administration [1]. Particularly, during the corona pandemic which energy demand of the hospitals increased. According to the growth of the world’s population and increasing total energy requirement, supplying energy through fossil fuel resources is getting off the market [4].

Although European Union aimed to reduce carbon emissions by at least 55% by 2030, a great portion of the energy supply of hospitals and health care centers is provided through fossil fuel resources [5,6]. Utilizing fossil fuels release $2.13 \times 10^9$ tons/year CO2 in the atmosphere [7]. Respirable particles are the result of the incomplete combustion of fossil fuels and are one of the main reasons for lung cancer [8]. These particles increase the chance of carcinoma up to 50% and consequently sever Covid illnesses [8,9].

During the COVID-19 pandemic emission of greenhouse gases, CO2, CO, and other pollutants reduce to a lower level in comparison with the pre-COVID-19 level. Also, average electricity and natural gas consumption decreased 4.46% and 10.35%, respectively [10]. However, energy consumption in the residential and medical sectors increased [10]. Hence, Rita et al. [11] recommended preserving the COVID-19 pandemic era environmental impact and reducing energy costs by investing in renewable energy resources as an alternative to fossil fuel energy resources for various countries’ energy needs.

To address the mentioned concerns, hybrid renewable energy systems can be utilized for providing energy demand of the health care centers and hospitals [12]. The main aim of hybrid renewable systems is to compensate for required energy and reduce dependency on fossil fuels. Although integration of hybrid renewable energy systems (HRES) into the buildings is well studied [13–15], integration of HRES in hospitals and medical buildings have not adequately been investigated. For
instance, a micro-hydropower system was designed for Lukla hospital, located in Sol Khumbu, Nepal to generate all its required energy [16]. However, due to the lack of power during the winter, a solar PV power plant was considered for the hospital in order to avoid unnecessary closure of the hospital during winter [16]. Pina et al. [17] investigated the importance of legal conditions for employing of HRESs in a cogeneration system for the building. The case study of the mentioned work was a Brazilian hospital and the results indicated that natural gas cogeneration system is an applicable solution for providing hospital’s demand energy. The mentioned paper highlighted that net present and operational cost are the main decision factors for considering a hybrid system for rural hospitals. Chowdhury et al. [18] analyzed the implementation and Levelized cost of an HRES for a temporary medical center in Saint Martin Island. Proposed HRES comprised of PV, wind turbine and battery and generates 27% less CO\textsubscript{2} than a fossil fuel-based system.

Proposed HRES comprised of energy generation, energy storage, and backup systems. All the off-grid hybrid renewable energy systems require a storage system for providing energy during the lack of renewable resources. Otherwise, the reliability of the system decreases which results in a shortage of energy during some specific hours. Electricity reliability is one of the greatest concerns of hospitals, therefore, a capable storage system needs to be considered for hospitals. To overcome argued issue, various energy systems are defined. Batteries, Hydrogen storage, and hydro-pump storage are discussed in the work of [19,20]. Due to the sake of the recent research, providing Oxygen demand of hospitals, the hydrogen storage system is considered for the proposed HRES.

The proposed system has been simulated in Iran’s climate conditions. Iran is a country that has a great potential for the construction of renewable energy infrastructures due to its diverse geographical conditions. Confirming to the reports Iran has 280 sunny days per year and the average annual solar radiation is 4.7 kWh per square meter and the yearly average of wind energy is estimated at 6500 MW. Compared to the green opportunity in Iran, renewable resources do not have an adequate and significant role in generating energy. Achieved data from studies in 2018 indicate that only 0.58% of demand energy in Iran came from renewable resources [21]. Hence, it is aimed to increase the proportion of renewable energy in annual energy generation.

In the current research, a novel method of generating required Oxygen for the COVID-19 patients has been introduced. In addition, the energy demand of the hospital wards which cope with COVID-19 patients has been provided through renewable resources. The proposed hybrid renewable energy system is comprised of three main parts, the renewable energy generator, the energy storage unit, and the controllers. Renewable energy is generated from photovoltaic panels and Alkaline electrolyzer, compressor, hydrogen storage tank, hospital oxygen capsules, and fuel cells form the energy storage part. Proposed HRES is simulated in TRNSYS software and hospital building has been simulated in OpenStudio + EnergyPlus. Finally, the optimum amount of power from the grid, cost rate, CO\textsubscript{2} emissions, and Oxygen production is calculated through a neural network genetic algorithm in MATLAB.

The following bullet items are the major contribution of this research paper:

- Modeling a prototype hospital building of Department of Energy (DOE) in OpenStudio and Energyplus software
- Calculating energy consumption of the wards which cope with COVID-19 infection
- Simulation and modeling of an HRES consisting of photovoltaic panels, electrolyzer, hydrogen tank, fuel cell, and controller device in TRNSYS
- Assessing the system capability in filling Oxygen capsules for COVID-19 patients and reducing dependency on grid power
- Optimizing HRES design with the neural network–genetic algorithm method and finding the optimum amount of CO\textsubscript{2} emissions, Oxygen production, cost rate, and demand power from the grid
- Calculating optimum sizing of PV panels, electrolyzer and fuel-cell power

2. System description

The present paper aims at providing energy demand of the hospital wards, which are dealing with COVID 19 patients, through renewable resources and oxygen demand of COVID 19 patients. Therefore, the HRES which comprises photovoltaic panels, an alkaline electrolyzer unit, compressors, Oxygen capsules, Hydrogen storage tanks, alkaline fuel cells, and controllers have been proposed.

PV panels generate electricity to compensate for the demand energy of the hospital wards which are dealing with COVID-19 patients. The controller is responsible to check and adjust all of the parameters
together. These parameters are generated energy, load, hydrogen tank pressure level, rated and idle power of electrolyzer, rated and idle power of fuel cell (idle power is the minimum power of electrolyzer or fuel cell that makes them able to continue working). The controller compares the amount of generated energy with demand, if the generated energy is higher than the demand energy, surplus energy initiates the electrolyzer so as to produce hydrogen. In this case, the controller checks whether the hydrogen tank has adequate volume to store hydrogen. If the mentioned conditions were satisfied, the electrolyzer is initiated and produced hydrogen and oxygen and if not, the system is able to sell the excess produced energy to the grid. Produced hydrogen and oxygen pass through a hydrogen compressor and oxygen compressor to reach the determined pressure. Then, oxygen and hydrogen are store in the oxygen capsules and hydrogen storage tank, respectively. Produced oxygen is used to provide demand oxygen for the COVID-19 patients.

In the case that controller detects the amount of produced energy is less than the load, the stored hydrogen can be utilized through a fuel cell in order to provide building demand. If the generated renewable energy is not sufficient to cover the energy demand of the Covid-19 hospital wards, the alkaline fuel cell generates the remaining electrical energy by utilizing stored hydrogen in the hydrogen storage tank. If the generated electricity via fuel cell is not able to cover the remaining electrical energy, electrical power will be bought from the grid.

A schematic of the hybrid renewable system is depicted in Fig. 1.

2.1. Building modeling

A prototype hospital building has been modeled based on the regulation of the department of energy (DOE) in OpenStudio and EnergyPlus. The mentioned building has a basement and 5 floors that contain 55 wards, the rooftop area of the hospital is 3377 m$^2$ and the total area of the hospital is 22,436 m$^2$. The hospital has a capacity of 767 people. Modeled hospital has 6 COVID-19 wards which include three intensive care patient rooms, an ICU, and an ICU nurse station. The building has a central chilled water loop and a central hot water loop that operates with the Variable Air Volume (VAV) HVAC system. This system is...
designed to keep the temperature of the building at 21 °C during winter and 24 °C during summer. The HVAC system also contains a fan, a humidifier, and a heating coil to provide comfortable conditions for the individuals.

Each intensive care room has the capacity of one person and ICU has the capacity of serving 33 people. The nurse station of the ICU ward with the capacity of 10 individuals needs to be considered in our modeling while it is a part of the ICU. Electrical equipment in the ICU station is different from other parts of the ICU, therefore, the ICU nurse station has been considered separately.

It is significant to generate enough cooling load for keeping vaccines at a safe temperature. Pfizer-BioNTech vaccines need to be stored between 25 °C and 15 °C for up to two weeks \[22\]. They can be kept between +2 °C and +8 °C before dilution. Hence, refrigerators’

| Table 1: Features of PV panels. [24] |
|--------------------------------------|
| Parameter                             | Unit | Value  |
| Number of modules in series             | –    | 1      |
| Number of modules in parallel           | –    | 976    |
| Module area (m²)                        |      | 1.822  |
| Short-circuit current at reference conditions (A) | | 11.4   |
| The open-circuit voltage at reference conditions (V) | | 41.9   |
| Reference cell temperature (°C)        |      | 25     |
| The voltage at max powerpoint and reference conditions (V) | | 34.1   |
| Module current at max powerpoint and reference conditions (A) | | 11     |

Table 2: Features of the hydrogen storage system and oxygen capsules.

| Component                | Parameter                             | Unit | Value  |
|-------------------------|---------------------------------------|------|--------|
| Fuel cell               | Number of cells in series             | –    | 70     |
|                         | Number of cells in parallel           | –    | 3      |
|                         | Maximum allowable current density (mA/cm²) |      | 680    |
|                         | Maximum allowable operating temperature (°C) | | 85     |
|                         | Thermal time constant (s)             | –    | 108    |
|                         | Electrolyzer pressure (bar)           |      | 7      |
|                         | Operating temperature (°C)            |      | 80     |
| Electrolyzer            | Number of modules in series           | –    | 64     |
|                         | Number of modules in parallel         | –    | 16     |
|                         | Electrode area (cm²)                  |      | 100    |
|                         | Faraday efficiency (mAh/m²)            |      | 0.988  |
|                         | Open circuit voltage (V)              |      | 5.6    |
|                         | Minimum allowable cell voltage (V)    |      | 0.4    |
|                         | Stack operating temperature (°C)      |      | 70     |
| Hydrogen Tank           | Min pressure (bar)                     |      | 7.1    |
|                         | Max pressure (bar)                     |      | 250    |
|                         | Tank volume (m³)                      |      | 2      |
|                         | Initial pressure level (bar)           | –    | 0.2    |
|                         | Gas temperature (°C)                   |      | 20     |
| Oxygen capsule          | Pressure (bar)                        |      | 138.9  |
|                         | Oxygen capacity (liter)                |      | 425    |
|                         | Weight (kg)                           |      | 2.49   |
| Compressor              | Number of compressor stages           | –    | 3      |
|                         | Gas inlet pressure (bar)              |      | 7      |
| Controller              | Fuel-cell idling power (kW)           |      | 17.9   |
|                         | Fuel-cell rated power (kW)            |      | 179.0  |
|                         | Electrolyzer idling power (kW)        |      | 17.12  |
|                         | Electrolyzer rated power (kW)         |      | 171.2  |
|                         | Tank upper limit (% of nominal)       | %    | 90     |
|                         | Tank lower limit (% of nominal)       | %    | 10     |

Table 3: Relation for calculating purchased cost of PV panels, electrolyzer and fuel cell [34,35].

| Component                | Parameter                             | Unit | Value  |
|-------------------------|---------------------------------------|------|--------|
| PV panels               | Number of PV                          | 120  | 1204   |
| Fuel cell               | Power (kW)                            | 120  | 1200   |
| Electrolyzer            | Power (kW)                            | 120  | 1200   |

Table 4: Parameters used for the optimization [41].

| Parameter                             | Unit | Value  |
|---------------------------------------|------|--------|
| CO₂ grid  RE CO₂/kWh                | g-CO₂/kWh | 5.9    |
| CO₂ grid  RE CO₂/kWh                | g-CO₂/kWh | 653    |
| Maintenance factor (Φ)               | –    | 1.06   |
| Annual operation hours (N)           | –    | 7000   |
| Operation years (ny)                 | –    | 20     |
| Interest rate (i)                    | –    | 12%    |

Table 5: Variation range of decision variables.

| Decision variable | Lower bound | Upper bound |
|-------------------|-------------|-------------|
| Number of PV      | 120         | 1204        |
| Fuel cell power   | 50 kW       | 500 kW      |
| Electrolyzer power| 120 kW      | 1200 kW     |

Table 6: Fraction of crossover, elite, and mutation.

| Parameter                             | Value  |
|---------------------------------------|--------|
| Crossover fraction                    | 0.8 x population size |
| Elite fraction                        | 0.05 x population size |
| Mutation fraction                     | population size (Crossover fraction + Elite fraction) |
temperature are designed between –23 °C and 5 °C.

In the computation of the energy consumption of the hospital, the energy consumption of the plant has been considered. Plant refers to all the equipment which are essential for the refrigeration system, such as the condenser, compressors, and other necessary equipment like pumps and fans in various parts.

The described hospital has been modeled in Tehran, Iran with a geographical location of (35.6892° N, 51.3890° E). Tehran has hot and arid summers and cold and dry winters also most of the days have clear weather conditions. Weather data of Tehran has been gained from Meteonorm at main weather stations in Mehrabad. Hourly solar radiation and ambient temperature for a year are depicted in Fig. 2.

2.2. Hybrid renewable energy system

In the proposed system, photovoltaic panels are used as the generator of energy and installed all over the roof area. PV panels have a rated power of 375 W and an area of 1.822 m² also they are placed in 65% of the roof area to avoid being exposed to other panels’ shading and have enough area for other solar equipment [23]. The technical characteristic of PV panels is given in Table 1.

The simulated energy storage system comprises alkaline electrolyzers with rated and idle power of 171.2 kW and 17.12 kW, respectively; The above-mentioned range is calculated by multiple simulations of the system and the recommended electrolyzer power rate from TRNSYS manuscript., in a way to satisfy system conditions. Electrolyzer utilizes electricity to produce hydrogen and oxygen from water. Produced hydrogen passes through a three-stage hydrogen compressor to reach the storing pressure and then it stores in the hydrogen tank with the capacity of 6 m³. Since the system operates transiently, it is necessary to select an appropriate volume for the hydrogen tank. The hydrogen tanks must have sufficient capacity to provide the necessary hydrogen for the operation of the fuel cell in idle mode. In addition, the hydrogen tanks have a capacity of 125.16 kg of hydrogen at maximum pressure and volume. Oxygen follows the same procedure and is stored in the medical storage cylinders. The main reason for using HSS is to store electricity through an environmentally friendly method that produces oxygen as a byproduct after COVID-19. These capsules are portable and can be transported to other hospitals when the produced oxygen exceeds the hospital’s needs. Medical gas cylinders are available in different shapes and volumes, the Oxygen capsules that are used in this study have a D-type medical gas cylinder which has a volume of 425 L and a pressure of 138.9 bar [25]. The purity of oxygen in oxygen capsules should not be less than 99.5% and the amount of carbon dioxide, carbon monoxide, and water should not be more than 300 ppm, 5 ppm and 67 ppm, respectively [26]. Chosen oxygen capsules can be kept at room temperature [27]. The design characteristic of simulated fuel cell and electrolyzer has been taken from the standard design value of TRNSYS-18 [28] and Kamel et al. [29] publications. The number of cells in parallel and series connections was chosen based on the polarization curve so that the ohmic potential is satisfied. In addition, a three-stage compressor is considered because a large compression ratio must be achieved and a single-stage compressor cannot achieve the required compression ratio.

Simulation of each component has been accomplished in TRNSYS-18. The technical characteristic of all the energy storage components and oxygen tanks are given in Table 2. The configuration of PV systems on the roof of the hospital is shown in Fig. 3. The proposed configuration is chosen based on the tilt angle of Tehran and the solar elevation angle ([30, 31]) to reduce the shadow effect. In addition, the space for the installation of other building equipment is also considered.

2.3. Optimization

After simulation of the system, the lowest cost rate, minimum CO₂ emissions, least power from the grid, and highest O₂ production is computed through the optimization method. CO₂ and cost rate are calculated based on Equations (1) and (2), respectively [32].

\[
CO_2 = CO_{2,grid} \times P_{grid} + CO_{2,RE} \times P_{ele} + CO_{2,comp} \times P_{comp}
\]  

\[
Z = Z \times CRF \times \Phi
\]

Where \( P_{ele} \) and \( P_{grid} \) stand for gained power from renewable energies and the grid (kWh) and \( CO_{2,grid} \) and \( CO_{2,RE} \) and \( CO_{2,comp} \) describe the life cycle CO₂ production of each kWh energy from renewable energies and the grid [33]. CRF, N, \( \Phi \), \( Z \) and \( \Phi \) are the capital recovery factor, the annual operation hours, the maintenance factor, Purchase cost and cost rate, respectively. Purchased cost of PV panels, electrolyzer, fuel cell, compressors, hydrogen tank, and also oxygen sell price is given in Table 3. In this table, \( n_{pv} \) represents the number of PV panels, \( P_{ele} \), \( P_{pv} \), and \( P_{comp} \) stand...
for electrolyzer, fuel cell and compressors power in kW, respectively. The $m_{H_2}$ in the Hydrogen tank is the maximum mass of $H_2$ in kg. Mass of $O_2$ is also calculated in kg. The dollar/euro exchange rate in February 2022 is set at 0.89.

$CRF = \frac{i(1+i)^n}{(1+i)^n-1}$  \hspace{1cm} (3)

Where $i$ and $n$ are interest rate and operation years, respectively. Value of the mentioned parameters are given in Table 4.

Grid power refers to the situation in which generated energy from PV panels and Fuel cells is not adequate to cover the energy demand of the building therefore remaining power is gained from the grid.

Fuel cell power, electrolyzer power, and the number of solar panels are the decision variables. These variables determine the optimum amount of CO2 and O2 production, cost rate, and grid power. The maximum number of 1204 PV panels can be installed on the rooftop of the hospital, based on Equation (4). Thus, the variation range of PV panels is between 120 and 1204. Fuel cell and electrolyzer power are selected based on their effectiveness during lack of the solar power, to reduce energy demand from the grid power. Increment of the electrolyzer and fuel cell power has a limitation and further increase in their power causes an increase in energy demand from the grid power, the reason behind this is that by increasing rated power, the idle power of fuel cell and electrolyzer increases and they become oversized. On the other hand, If the power of the fuel cell and electrolyzer sets below these values, they almost have zero effect on the system so they have been chosen as minimum values. Hence, after simulation of the system and iteration of calculation, the variation ranges of electrolyzer power and fuel cell power are computed. The variation ranges of each decision variable are given in Table 5.

$PV$ panel number $= \frac{(A_{nod} \times 0.65)}{A_{PV}}$ \hspace{1cm} (4)

In the present work, the optimization procedure of the system is performed with the genetic algorithm (GA). As the simulation has been done in TRNSYS-18 and TRNSYS-18 cannot perform multi-objective optimization, a neural network – genetic algorithm method is proposed. Neural network – genetic algorithm consists of three steps, generating input data with Sobol algorithm, training the neural network, and optimizing trained model with genetic algorithm. Sobol algorithm generates input data files for different amounts of PV panels, electrolyzer, and fuel cell power. Then, the generated file is given to TRNSYS-18 to calculate the grid power and oxygen production. The cost rate and CO2 emissions of each set of input data are calculated in MATLAB. Finally, the dataset for the neural network is completed. Afterward, the dataset is trained by the machine learning algorithm. The trained model calculates CO2 emissions, cost rate, $O_2$ production, and grid power concerning the number of PV panels, electrolyzer, and fuel cell power. Eventually, a genetic algorithm is employed on the trained model to calculate the optimum value of cost rate, CO2 emission, $O_2$ production, and required power from the grid. Each step is defined in detail in the following sections.

2.3.1. Sobol algorithm

To have an efficient and accurate neural network, a large dataset is required. As the size of the dataset increases, the accuracy of the model increases, too. Therefore, for generating an acceptable dataset, an input file is generated with 2000 data. To have a random dataset with the best scatter, the Sobol algorithm is employed. Sobol algorithm provides quasi-random numbers of PV panels, electrolyzer, and fuel cell power in the mentioned range in Table 3. Hence, the input data file has a smooth distribution of PV panels, electrolyzer, and fuel cell power.

Afterward, the generated input data file is given to TRNSYS-18 for calculating the grid power and $O_2$ production. Eventually, the dataset is prepared to be used in Artificial Neural Network (ANN).

2.3.2. Train artificial neural network

Preprocessing of data is an important step for dealing with datasets.

Table 7

| Floor | Zone name/system name | Percentage of electricity load [%] |
|-------|-----------------------|-----------------------------------|
| Basement | Basement              | 4.343                             |
| Floor 1 | Corridor              | 0.583                             |
| Floor 1 | Emergency room exam 1 | 0.357                             |
| Floor 1 | Emergency room exam 2 | 0.357                             |
| Floor 1 | Office                | 0.103                             |
| Floor 1 | Emergency room nurse station lobby | 2.667                          |
| Floor 1 | Emergency room trauma 1 | 0.158                           |
| Floor 1 | Emergency room trauma 2 | 0.158                           |
| Floor 1 | Emergency room triage | 0.412                             |
| Floor 1 | Lobby records         | 0.842                             |
| Floor 2 | Corridor              | 0.583                             |
| Floor 2 | ICU                   | 2.569                             |
| Floor 2 | ICU nurse station      | 1.814                             |
| Floor 2 | Intensive care patient room 1 | 0.577                         |
| Floor 2 | Intensive care patient room 2 | 0.101                         |
| Floor 2 | Intensive care patient room 3 | 0.452                         |
| Floor 2 | Operation room 1       | 0.344                             |
| Floor 2 | Operation room 2       | 1.718                             |
| Floor 2 | Operation room 3       | 0.344                             |
| Floor 2 | Operation room 4       | 1.375                             |
| Floor 2 | Operation room nurse station | 1.905                          |
| Floor 3 | Corridor north-west   | 0.581                             |
| Floor 3 | Corridor south-east    | 0.581                             |
| Floor 3 | Laboratory            | 1.237                             |
| Floor 3 | Nurse station lobby    | 1.704                             |
| Floor 3 | Patient room 1         | 0.490                             |
| Floor 3 | Patient room 2         | 0.082                             |
| Floor 3 | Patient room 3         | 0.474                             |
| Floor 3 | Patient room 4         | 0.082                             |
| Floor 3 | Patient room 5         | 0.490                             |
| Floor 3 | Patient room 6         | 0.065                             |
| Floor 3 | Patient room 7         | 0.474                             |
| Floor 3 | Patient room 8         | 0.065                             |
| Floor 3 | Physiotherapy         | 0.921                             |
| Floor 4 | Corridor north-west   | 0.581                             |
| Floor 4 | Corridor south-east    | 0.581                             |
| Floor 4 | Laboratory            | 1.237                             |
| Floor 4 | Nurse station lobby    | 1.704                             |
| Floor 4 | Patient room 1         | 0.490                             |
| Floor 4 | Patient room 2         | 0.082                             |
| Floor 4 | Patient room 3         | 0.474                             |
| Floor 4 | Patient room 4         | 0.082                             |
| Floor 4 | Patient room 5         | 0.490                             |
| Floor 4 | Patient room 6         | 0.065                             |
| Floor 4 | Patient room 7         | 0.474                             |
| Floor 4 | Patient room 8         | 0.065                             |
| Floor 4 | Radiology             | 4.824                             |
| Floor 5 | Corridor              | 0.514                             |
| Floor 5 | Dining                | 0.957                             |
| Floor 5 | Kitchen (Kitchen includes vaccines refrigeration system) | 7.967 |
| Floor 5 | Nurse station lobby    | 1.958                             |
| Floor 5 | Office 1              | 0.077                             |
| Floor 5 | Office 2              | 0.483                             |
| Floor 5 | Office 3              | 0.077                             |
| Floor 5 | Office 4              | 0.116                             |
| Whole building | Exterior lights | 1.041                           |
| Whole building | Exterior equipment | 12.460                          |
| Whole building | HVAC                 | 18.033                           |
| Whole building | Plant                | 16.229                           |
| Whole building | Refrigeration         | 0.231                             |
| All COVID-19 systems and zones | 29.64 |
set. Hence, the dataset is preprocessed with Equation (5).

\[ X = \frac{x - \text{mean}(x)}{\text{std}(x)} \] (5)

where \(x\), \(X\), \(\text{std}(x)\), \(\text{mean}(x)\) refer to features before preprocessing, features after preprocessing, standard deviation, and the average value of each feature.

Supervised machine learning with the help of ANN has been utilized. 80% of preprocessed data are classified as train data, 10% as validation data, and the remaining 10% as test data. The proposed neural network consists of 50 \(\times\) 50 neural layers and weight and bias are calculated based on the fastest backpropagation algorithm in MATLAB. Hence, the Levenberg-Marquardt optimization method in the MATLAB toolbox has been employed. Mean Square error is accounted as a cost function for evaluating the effectiveness of the model. Mean square error is calculated from the following Equation (6).

\[ \text{MSE} = \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \] (6)

Where \(n\), \(y_i\), and \(\hat{y}_i\) denote to the number of data, actual and estimated value, respectively.

### 2.3.3. Genetic algorithm

As it was discussed earlier, genetic algorithm optimization is employed on the trained model from ANN. Population size in the Genetic Algorithm has a significant factor that affects the ability to search among data. As the population size increases, the accuracy of converging to an optimal solution increases, too. However, population size has a direct relation to the number of decision variables. Hence, the population size has been set to 50. Mutation, elite, and crossover factors that define the portion of each variation in the next generation are listed in Table 6. Mutation, crossover, and elite fraction refer to random small changes in population, the fraction of the next generation, and the fraction of initial population size, respectively.

### 3. Result and discussion

Modeling of the building has been accomplished in OpenStudio 1.0.0 and EnergyPlus 9.4.0. HRES has been simulated in TRNSYS18. Genetic algorithm – neural network optimization has been done in MATLAB R2021a.
3.1. Building analysis

Fig. 4 indicates the portion of gas and electricity consumption of the modeled hospital. As it is demonstrated, 77.1% of whole energy consumption is due to the electrical need of the building and only 22.9% of the energy requirement of the hospital is supplied with natural gas. As it is clear, the interior equipment of the hospital requires the greatest portion of energy around 34%; this is because each ward of the hospital has sophisticated medical equipment which is mainly driven by electricity. The second electricity consumer part of the hospital is interior lighting, which is responsible for 16.92% of total electrical consumption. Natural gas is generally utilized for interior equipment, heating facilities, and water system, however, 2% of the heating demand of the building is supplied through electricity.

As it was discussed, energy consumption of COVID-19 wards is considered. In Table 7 contribution of energy consumption of each ward of the hospital is listed. Then colored rows show the sections and wards that deal with COVID-19. Therefore, 29.64% of the whole hospital energy consumption is served in sections that coped with corona patients, annually. The mentioned portion of the energy is going to be covered by renewable resources.

3.2. System analysis

Simulated HRES is supposed to annually cover 29.64% of the whole electrical consumption of the building which is 5,668,393 kWh. At first proposed system consists of 976 PV panels and generates 46% of the energy demand of the required energy. The remaining energy is gained from the grid power. After considering an ESS for the renewable facility, the amount of energy that can be sold to the grid reduces to $9.304 \times 10^4$ kWh annually. While the proposed system with hydrogen ESS covers 76% of the demand energy of the hospital. Monthly energy trend is shown in Fig. 5.

By having a hydrogen ESS, not only less amount of electricity is required from the grid but also oxygen can be produced for filling the oxygen capsules and fulfilling the oxygen requirement of the hospital. Between March to June, the number of filled Oxygen capsules can be filled monthly. From March to June, the number of filled Oxygen capsules reaches its maximum while a greater portion of excess renewable energy is generated. The number of filled capsules reaches its maximum in May, this is because the energy demand of the building in this month has a different pattern from the generated energy, hence, more electricity goes through the electrolyzer. This means that in 256 h of May generated renewable energy exceeds the demand energy, thus, it is transferred to be stored in ESS. Therefore, the electrolyzer works further in May compared to other months and fills more oxygen capsules. Fig. 6 displayed the described trend.

3.3. Optimization

After the simulation of the energy system, an optimization algorithm with a neural network-genetic algorithm is employed on the simulated system to compute the lowest cost rate, minimum CO$_2$ emissions, the least grid power, and highest O$_2$ production with an optimal number of PV panels, electrolyzer, and fuel cell power. Hence optimization procedure is divided into two sections, neural network and genetic algorithm.

3.3.1. Neural network

To train the best ANN model on the dataset, the learning algorithm iterates through the entire dataset multiple times. Therefore as the number of epochs increases, the accuracy of the model on the trained data increases. However, after a certain number of epochs, the accuracy of the model on the validation data decreases due to the overfitting of the model Validation failure applies to the situation in which the cost function of validation data in the current epoch is higher than the minimum cost function of validation data in previous epochs. Therefore, the threshold of 6 validation fails has been considered for this research;
Fig. 8. Train, validation, and test mean square error with epochs.

Best Validation Performance is 0.0015883 at epoch 21

Fig. 9. Regression model for training, validation, test and all data.
This is because increment of the cost function can occur in some epochs due to random fluctuations. However, if the increment of the cost function grows to more than 6 epochs in a row, the learning algorithm of the model stops, and the epoch with the lowest cost function will be selected as the optimum number of epochs. Described procedures are displayed in Fig. 7 and Fig. 8. The optimum number of epochs is 21 and the mean square error of the validation dataset is 0.0015883 which is the minimum amount.

To evaluate the accuracy of the model and the relation between actual and predicted results, the correlation coefficient is defined. The correlation coefficient formulates the relation between actual and predicted results, the closer coefficient is to 1, the better the ANN model predicts the results. Correlation between predicted and actual results of the validation, test, train, and all data are given in Fig. 9. Fig. 9 indicates that the correlation between actual and predicted data is 0.99831, which means that the ANN model has been perfectly fitted to the data and can precisely predict the cost rate, CO2 emissions, grid power, and O2 production based on any given set of the number of PV panels, electrolyzer, and fuel cell power.

3.3.2. Genetic algorithm

The main aim of employing a neural network is to generate an energy model that makes it possible to employ the genetic algorithm optimization method on it. This means that by having any set of input data, which constitutes of the number of PV panels, electrolyzer, and fuel cell power, the output of the system which is CO2 and O2 production, cost rate, and the grid power is calculable. After training the ANN model, the genetic algorithm is applied to the trained neural network. The results of the GA are shown in Fig. 10. In Fig. 10, power from the grid and CO2 emissions are shown on the X-axis, cost rate is displayed on the Y-axis and the number of oxygen capsules is shown based on the size and color of the bullets. As the size of the bullet increases, the number of produced

![Fig. 10. Pareto frontiers of 4 objective optimizations (cost rate, CO2 emission, power from the grid, and number of oxygen capsules).](image)

| Table 8 |
|---------|
| The number of PV panels, electrolyzer power, fuel cell power, CO2 emissions, filled O2 capsules, cost rate and power from the grid for each point. |

| Point | Fuel cell power [W] | Electrolyzer power [W] | Number of solar panels [\text{-}] | Power from grid per year [MWh/year] | CO2 emission per year [kg/year] | Number of produced O2 capsules per year [\text{-}] | Cost rate [EUR/hr] | Importance |
|-------|---------------------|------------------------|--------------------------------|-----------------------------------|--------------------------------|--------------------------------|----------------|------------|
| A     | 50,033              | 120,364                | 502                            | 1668.85                           | 1,098,169                      | 7409                           | 8.470          | Minimum Cost |
| C     | 309,958             | 894,602                | 1177                           | 47.22                             | 40,704                         | 237,765                       | 44.450         | Minimum power from grid per year |
| D     | 258,627             | 1,025,645              | 1185                           | 115.39                            | 85,158                         | 272,228                       | 44.560         | Maximum O2 production |
| B1    | 179,048             | 171,209                | 976                            | 469.07                            | 315,793                        | 67,833                        | 18.930         | Best point considering cost and power from grid |
| B2    | 124,734             | 801,523                | 1172                           | 811.59                            | 539,150                        | 217,292                       | 31.109         | Best point considering cost and O2 production |

This is because increment of the cost function can occur in some epochs due to random fluctuations. However, if the increment of the cost function grows to more than 6 epochs in a row, the learning algorithm of the model stops, and the epoch with the lowest cost function will be selected as the optimum number of epochs. Described procedures are displayed in Fig. 7 and Fig. 8. The optimum number of epochs is 21 and the mean square error of the validation dataset is 0.0015883 which is the minimum amount.

To evaluate the accuracy of the model and the relation between actual and predicted results, the correlation coefficient is defined. The correlation coefficient formulates the relation between actual and predicted results, the closer coefficient is to 1, the better the ANN model predicts the results. Correlation between predicted and actual results of the validation, test, train, and all data are given in Fig. 9. Fig. 9 indicates that the correlation between actual and predicted data is 0.99831, which means that the ANN model has been perfectly fitted to the data and can precisely predict the cost rate, CO2 emissions, grid power, and O2 production based on any given set of the number of PV panels, electrolyzer, and fuel cell power.

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O₂ capsules increases, too. Points A, B1, B2, C and D are the most important points among the optimized points of the Pareto frontier which their exact characteristic and explanations have been mentioned in Table 8.

As is mentioned earlier, points A, B1, B2, C, and D are the most important optimized points and they are selected based on the minimum cost, best point based on cost rate and grid power, best point based on cost rate, and O₂ production, minimum power from the grid, and the maximum number of produced O₂ capsules. The number of PV panels, electrolyzer power, fuel cell power, CO₂ emissions, filled O₂ capsules, cost rate, and power from the grid for each point have been depicted in Table 8. Minimum cost occurs when CO₂ emissions and relatively the grid power is at their maximum points and also the produced oxygen is minimum. In this paper the main point is to reduce the dependency of the COVID 19 related wards of the hospital to the grid power, therefore in a shortage of electricity, these wards can keep working. Moreover, the other deciding factor for HRES set up in a hospital is to generate the required oxygen for the patients. Therefore, based on the regulations and budget of the hospital the set of PV panels, electrolyzer, and fuel cell power can be selected.

4. Conclusion

Specific wards and sections of the hospital which is located in Tehran, Iran, have been analyzed in this paper. These wards and sections are in close contact with COVID-19. The main aim of this paper is the generation of oxygen for use in hospitals by installing PV-cells to cover the energy demand of these sections through renewable resources with hydrogen ESS, and reduce dependency on grid power. Also, fewer CO₂ emissions and the minimum cost rate of each setup are the other significant decision factors. Therefore, a hybrid renewable energy system that constitutes PV panels and a Hydrogen energy storage system has been proposed. Afterward, based on the number of PV panels, electrolyzer, and fuel cell power, optimum results for CO₂ and O₂ production, cost rate, and the grid power has been achieved. The following main accomplishments of the paper are listed.

- A great portion of the electricity consumption of the hospital is due to interior and exterior equipment, which is similar for each month. Cooling and air conditioning facilities make a notable difference in electricity consumption each month. Hence electricity consumption of the hospital for each month is between 95,857 kWh and 179,280 kWh.
- ICU, three Intensive care patient rooms and ICU nursing station for nursing the COVID-19 patients, kitchen for storing the vaccine and plant section have been considered in this paper and all the mentioned parts are responsible for 29.64% of the whole hospital’s energy consumption.
- PV panels generate 46% of the annual energy consumption of the hospital. Also, with hydrogen ESS and PV panels, 76% of the annual demand energy of the hospital is covered by renewable resources.
- Demand energy of the hospital reaches its maximum from 8am to 2pm. The energy generation of the HRES is at its peak at 12 Am.

Credit author statement

Ali Izadi: Conceptualization, Methodology, Software, Validation, Writing – original draft. Masoomeh Shahafve: Methodology, Software, Validation, Writing- original draft. Pouriya Ahmadi: Conceptualization, Supervision, Validation, Writing – review & editing. Pedram Hanafi-zadeh: Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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