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Optimization of tribrid energy systems for cost-effective and high-efficiency electricity generation

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ABSTRACT

Integrating renewable energy - fuel cells, wind turbines, and photovoltaics - introduces a viable way to improve power generation systems' efficiency and dependability. The purpose of this study is to look forward to integrat fuel cells and photovoltaic panels to maximize wind turbine performance at the Zafarana wind farm. Zafarana, an Egyptian location, is a noteworthy destination for renewable energy due to its strong wind resources. The research's design intends to increase energy production, enhance system efficiency, and establish a more stable power output profile by merging wind energy with PV and fuel cell technologies. An analysis is created on different optimization methodologies and configurations, considering variable parameters like system costs, environmental impact, and resource availability.The suggested methodology algorithm design successfully reduced the net present cost (NPC) of electricity, demonstrating a significant improvement over conventional optimization methods. The approach was to decrease the NP (net present) amount to determine the cost value, supported using LPSP (loss of power supply probability).The output power could be changed by these control schemes to meet predetermined levels by using MATLAB\Simulink program, a TRIBRID-local grid (LG) system in the ZAFRANA plant subject will be modeled, with the addition of PV system and fuel system sources to feed residential loads, local grid, and desalination unit considered as an objective function. The best solution will be found by applying an enhanced optimization method modified firefly algorithm (MFFA).The consequence of the research will be figured to achieve a cost-effective and high-efficiency electricity generation solution. Advanced optimization methodology, such as the modified firefly algorithm (MFFA), is utilized to assess the integration of these renewable sources, aiming to enhance energy output while minimizing operational costs. The conclusion results indicate a significant improvement in Egyptian Local Grid of 2500 MW, 120 KV while maintaining the lowest power losses in the overall objective function, demonstrating that the synergistic combination of wind, fuel cell, and solar technologies can lead to an effective combined sustainable energy plant.

Keywords: TRIBRID power, fuel cell, electrolyzer, Zafarana, renewable energy, Simulink, desalination.

INTRODUCTION

The Zafarana wind farm, situated along Egypt's Red Sea coast, is a testament to the country's commitment to harnessing wind-renewable energy resource. With favorable wind conditions, Zafarana has emerged as a pivotal site for wind energy generation, contributing significantly to Egypt's renewable energy targets which has 340 MW total capacity wind power station and a 50 MW of PV system. There are 400 wind turbines on it, each with a 0.85 MW power rating. The wind turbines are based on the Gamesa G52/850 type, whose features are described in [Mekhamer, et al., 2024]. As the global shift towards sustainable energy intensifies, integrating multiple renewable technologies becomes increasingly imperative to enhance energy reliability, efficiency, and sustainability. This paper explores the best implementation and an optimized combination between fuel cell, photovoltaic (PV), and wind turbine technologies at the Zafarana plant. Each technology harvest energy with a different method. Wind turbines efficiently harness kinetic energy from wind currents, PV panels convert solar radiation directly into electricity, and fuel cells electrochemically convert hydrogen into electricity with high efficiency and low emissions. By synergistically combining these technologies, the aim is to create a TRIBRID energy system that leverages the complementary strengths of each component to maximize energy output and system performance.

Yemeli et al. [2024] has made an optimization and techno-economic feasibility multisource hybrid–off-grid systems such as fuel cell (FC), wind turbines, diesel generators, and photovoltaic systems to satisfy three realistic different loads: low, medium, and heavy activities located in Cameroon. Additionally, diesel generator/FC, PV/Diesel/FC, and wind/diesel generator/FC systems were compared regarding net present cost (NPC), cost of energy (COE), and loss of power supply probability (LPSP) and environmental emissions.

The findings showed that the photovoltaic/wind/diesel/FC system is the most cost-effective option for meeting the demands of the three categories of non-domestic loads, with corresponding NPC, COE, and LPSP values of 159319.4$, 1.087$/kWh and 0.0397 for heavy activity, respectively. These findings hold for a maximum (LPSP) of 5% and a minimum renewable energy sources fraction of 85%.

Akbar et al. [2018] has proceeded with an optimization and economic model created for grid-independent hybrid renewable energy systems (GIHRES) to meet load demand besides increasing freshwater availability.

The GIHRES integrates several systems like reverse, wind turbines, and hydrogen. Wind turbines/battery/reverse osmosis desalination (ROD), photovoltaic/wind/battery/ROD, solar/battery/ROD, osmosis desalination, and solar/wind/hydrogen/ROD. The outcomes are contrasted with those produced by the harmony search algorithm. According to the findings, GIHRES-based battery energy storage is more affordable than GIHRES-based hydrogen energy storage. The most economical energy system among the many GIHRES-based hydrogen energy storage options is the hybridization of photovoltaic power, hydrogen storage (fuel cell, electrolyzer, and hydrogen tanks), and reverse osmosis desalination at varying maximum loss of power supply probability (LPSP).

Ultimately, the modeling results show that, among several GIHRES, the hybrid photovoltaic/battery/reverse osmosis desalination system is the most reliable with an economical option to produce fresh water supply and satisfying load demand for varied LPSP. Additionally, it is demonstrated that the harmony search algorithm based on the minimum, maximum, mean, and mean simulation time (MST) indexes yields less advantageous results than the enhanced bee algorithm.

To determine the wind energy by considering the wind speed data that were gathered for 10 minutes at a height of 25 meters for four sites between 1991 and 1995. around the Suez Gulf. According to the results from Alham et al. [2023], the best substation layout in this concentration is Zafarana. Otherwise, as of 2019, Egypt's installed wind projects produced 580 MW at the Gulf of El Zaytin Egypt (using 2 MW wind turbines at 60 m height), 545 MW at the Zafarana site (using 700 wind turbines with rated powers of 600 kW, 660 kW, and 850 kW), and 250 MW.

He also presented that the average COE for Egypt and the rest of the world in 2019 was a mere 0.053 $/kWh and 0.03 $/kWh, respectively. Therefore, the power of wind energy is thoroughly evaluated for four specifically chosen sites in Egypt: Ras El-Hekma, Farafra, Nuweiba, and Aswan. Ras El-Hekma and Nuweiba are classified as temperate wind classes.

Over five years (2015–2020), data collected at one-hour intervals at a height of 10 meters above sea level were used to analyze the wind speed data. The equilibrium optimizer (EO) algorithm is used in each testing location to decide the ideal hub height for each chosen wind turbine.

The Weibull distribution function was used to determine the energy density of the four selected locations based on the anticipated ideal hub height for each wind turbine. The results showed that the maximum density of wind energy, achieved at the Ras El-Hekmasite using the SG 2.1–114 wind turbine, was 5207.9 kWh/m^2, this point was our challenge for showing that the Zafarana site could have the highest efficiency and power from renewable energy in Egypt with adding the COE differential cost between these studies However, he figures out that Ras El-Hekma has the lowest COE of any location, at 0.0092 $/Kwh.

Abdoulaye et al. [2024] suggested a method for carrying out an analysis of the techno-economic and environmental of photovoltaics, wind turbines, battery storage, and fuel cell systems in both on-grid and off-grid configurations to supply power. The Cuckoo Search Algorithm and the Non-dominate sorting genetic algorithm are two (2) meta-heuristic optimization techniques which he implemented and executed in countryside areas inside the framework of Chad utilizing using Matlab/Simulink program to achieve this goal.

The system self-sufficiency index (SSSI) beside annualized system cost (ASC) were selected as the objective functions to find the simulation for net present cost (NPC) of $2,107,900 (on-grid), $512,650 (off-grid), $2100 for the grid, 0.1457$/kWh (on-grid), 0.0538$/kWh (off-grid).

It would be helpful in the Zafarana site to calculate the best economy cost in a (grid-connected) search.

Abdelshafy et al. [2018]. has created a desalination plant to provide fresh water and electricity in Alexandria, Egypt's New Borg El-Arab neighborhood.

The particle swarm optimization – grey wolf optimizer optimization approach is the ideal size of the various system elements to reduce CO_2 emissions and the entire expense of delivering fresh water over 20 years.

He demonstrated that, while having the lowest cost and emissions from (photovoltaic, wind turbine, battery, and diesel), using HSS is more expensive as a storage system than BSS since the cost of producing water is 1.522 $/$m^3$ for HSS and 1.299 $/$m^3$ for the battery. So it takes these results to review and recalculate in the Zafarana site to figure the lowest cost of using back-power for producing power and water in desalination plants.

Additionally, by utilizing a combination of primary sources, including photovoltaic, wind, and fuel cells coupled to a grid system and providing a reverse osmosis desalination plant, Das et al. [2022], came very close to achieving the goal of this research. He began his quest by breaking down each primary source into its component parts. Then worked on fuel cell employment topologies and tactics, talking about different control systems, energy management, application areas, and performance.

Enhancing the power energy utilized in hydrogen applications is the among of the primary goals of this study's research. Hydrogen must be produced using renewable energy sources. Any renewable source system could be replaced by fuel cell technologies provided the process's shortcomings are fixed. Despite the research gap, the author's research in this publication was not influenced by any known competing financial interests or personal affiliations.

Wang et al. [2024] has figured the primary subject of the current research is to optimum HRES conformation with the energy source and model pricing with reliability in supplying a rural Turkish area with electricity. Various forms have been examined to provide the best shape.

The results of the subtraction-average-based optimizer (ISABO) process were compared with several other procedures that are handled using the firefly (FA) and PSO (particle swarm optimization) processes.

The objective was to decrease the system's NP (net present) amount to determine the cost value, which is supported by the LPSP (loss of power supply probability) which finally showed which suggested ISABO algorithm effectively decreased the levelized cost and net present cost (NPC) of electricity (LCOE) by 12%, demonstrating a significant improvement above traditional optimization methods.

Modu et al. [2024] has worked on a framework for the effective assessment of an independent (HRES) which being used to supply a rural community in northeastern Nigeria with electricity needs. The suggested micro-grid setup includes battery storage, fuel cells, biomass gasifiers, wind turbines, and solar photovoltaic systems.

Using genuine local weather information and the load demand throughout twelve months, the Levy flight-slap swarm algorithms (LFSSA) are used to predict the component sizes.

The goal of the optimization is reducing the annualized system cost (ASC) of the HRES even through taking probability of loss of power supply (LPSP) as a reliability constraint into account.

One of successful researchers, [Wang et al., 2021], has developed a hybrid system that integrates Stirling engines, fuel cells, solar, wind, and electrolyzer energy. Water electrolyzers are fed with power from specially designed PV and wind turbines. According to his research, the cycle's electrical efficiency is 56.9%, and the electrolyzer's main function is to collect hydrogen and oxygen gasses from fresh water.

this study's shortcoming was that it was carried out on a small rather than a large scale like Zafarana plant.

To provide the residential and commercial load in Iran with a highly reliable solar, wind turbine, and fuel cell system, Jahannoosh et al. [2021] supplied genuine data about radiation levels and wind speeds at a specific place. utilizing many algorithms, such as the grey wolf optimizer. Based on his findings, she discovered that the most dependable combination for conventional power plants is solar, wind turbine, and fuel cell. However, in her example study, the research employed flawless optimization using a range of values for the dependable power source. Otherwise, a flawless Zafarana site is not the best solution as it's not used in high loads.

To achieve a certain level of increased system efficiency and improved stability, Roy et al., [2022] provided a thorough review of PV-wind energy from the power mathematical modeling and power electronic converter topologies in bus connection (AC shunt bus – DC shunt bus – Multi-input coupled HES) in the hybrid system.

This study reviewed existing modeling and power converter designs for wind turbines-PV hybrid renewable systems, utilizing a variety of energy source combinations, modeling, and optimization methodologies. Additionally, he concentrated on the best design algorithms using super capacitors, the battery degradation model, and elementary mathematical modeling. Even if many advances in HRES have been made over the years, a thorough study aids in completing the technical requirements for connecting renewable sources to the grid.

Roy et al. [2022] utilizing tools like the multi-input converter (MIC), which has been developed and proposed in his search as a means of achieving both individual and simultaneous power transfer to the grid, would be highly beneficial at the Zafarana site. A single power stage can incorporate many energy storage technologies and renewable energy sources thanks to the MIC.

Naderipour et al. [2021] provided studies and analyses on the design of a hybrid fuel cell, photovoltaic, tidal, and wind for Iranian provinces of Gorgan, Urmia, and Yazd. Actual radiation and wind speed data are used to design affordable hybrid systems. He identified the ideal combination of reliable and reasonably priced devices for these areas in a range of setups.

Abdalla et al. [2022] added a desalination system using reverse osmosis (RO) and solar radiation, along with solid oxide fuel cells as he introduced a perfect compression between two case plants in Egypt (El-Arish and El-Zafarana) to take a special case study close to our search with the same 2000 Lt/d freshwater production capacity. Using MATLAB/Simulink, to obtain the results of both locations producing. Furthermore, the exact climatic and power data for the Egyptian city of Zafarana were found through a very useful search.

As far as we are aware, no literature has addressed the maximum high-efficiency use of fuel cells in conjunction with photovoltaic, wind, or electrolysis power plants for the Zafarana region. This paper's primary contributions include:

- Increasing and optimizing the energy generated by the Zafarana system through the addition of hybrid sources to feed the main grid and optimization under changeable conditions.
- By incorporating hybrid power sources with a hydrogen source, you may increase system efficiency with voltage and frequency stability and maximize energy in real-time at the lowest possible cost.
- Selecting the best optimum technique for objective function with fewer power losses and minimum cost of the tribird system.

THE PROPOSED MODELING TRIBRID SYSTEM OVERVIEW

The addition of photovoltaic, fuel cell, electrolyze, and desalination plants to the wind turbines in the Zafarana plant, as depicted in Figure 1, demonstrates the efficacy of control methods that will be verified by modeling and experimental testing utilizing this hybrid system under varied circumstances to fill the gap of the problem of lower power and high cost in Zafarana wind farm.

The Zafarana plant's hybrid system, which features larger turbines, better blade designs, and control systems to optimize power output and efficiency, is the product of advanced wind turbine technology. Finding the most cost-effective optimization technological way to produce energy through the addition of fuel cells and hydrogen tanks is the necessary research for this subject. This will guarantee the Egyptian electrical power grid a steady and dependable energy supply. Intending to maximize overall efficiency and dependability, hybrid system optimization uses integrated management and optimization algorithms to manage the integration of wind power with other energy sources (photovoltaic and fuel cells) in the tribrid power.

This research focuses on combining photovoltaic panels, a big wind turbine, an electrolyzer [Devrim, and Bilir, 2016], and proton exchange membrane fuel cells to improve electricity for the Zafarana region of Egypt. Solar and wind energy were the main energy sources in the site, besides

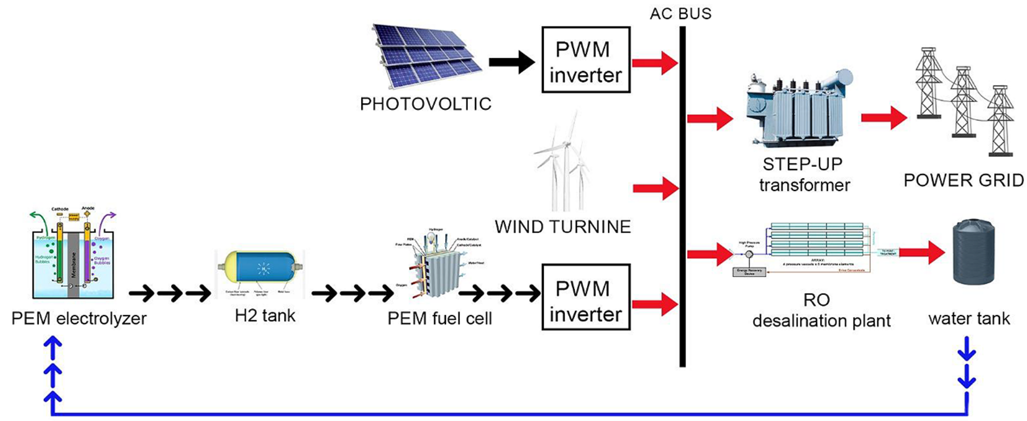


Figure 1. Blocks diagram of proposed tribrid system

proton exchange membrane fuel cells as a sustainable power source, the outcomes show that the tribrid system is capable of meeting the grid's annual electricity needs.

The designed model components

Modeling of wind turbine

Prominent wind turbine manufacturers, such as Vestas and Siemens Gamesa, implement life extension initiatives that establish the duration of the wind turbines' operation at the ZAFRANA plant [Salem et al., 2022]. The current study aimed to find the most effective method for evaluating the power plant connected to the Egyptian electricity network. It focused on the newest turbines, the double fed induction generator (DFIG) technology in Figure 2 [Das et al., 2022], that had been put in the region. It chose 142 Nordex WTs to provide 120 MW of electricity in total. Each turbine produced 850 Kw at a wind speed of 9 m/s and at a height of 25 m above ground. Equation 1 presents the mathematical models of DFIG-WT displayed. WT modeling The following formula can be used to explain the mechanical power collected by the blades that revolve with a swept area ($A = \pi R^2$):

$$P_m = ½\, C_p \rho \pi R^2 V_m^3 \quad (1)$$

where: R is the blade length (m), V_M is the wind speed (m/s), ρ is the air density (kg/m^3), and to determine C_p which is the power coefficient. The pitch angle (β) and tip speed ratio (λ) of blades [Abdelshafy et al, 2018, Abdalla et al., 2022]:

$$C_p = 0.5176 \left({}^{116}/_{\lambda_i} - 0.4\beta - 5 \right) e^{\frac{-21}{\lambda_i}} + 0.0068\,\lambda \quad (2)$$

Besides Δi is known as:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (3)$$

The tip speed ratio as:

$$\lambda = \frac{\omega_t \times R}{V_w} \quad (4)$$

The mechanical torque of a wind turbine, T_m, where ω_t is the turbine shaft's rotating speed in rad/s.

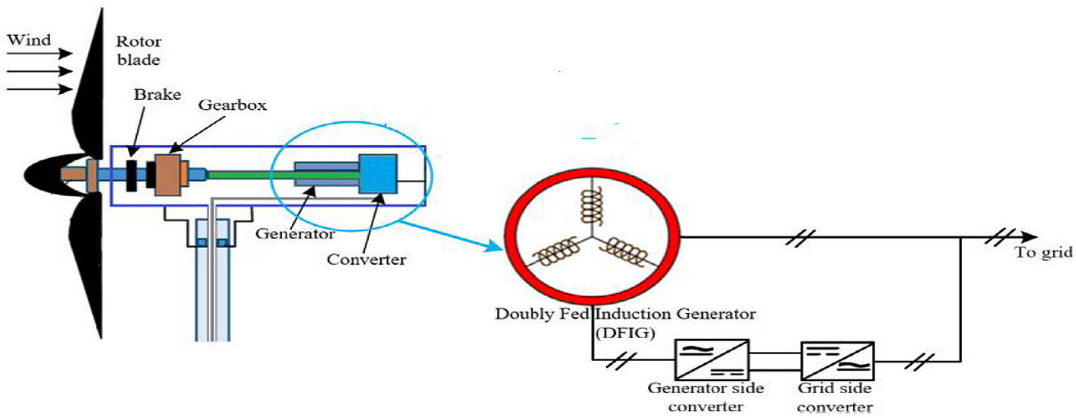


Figure 2. Blocks diagram of doubly fed induction generator [Das et al., 2022].

$$T_m = \frac{P_m}{\omega_t} \quad (5)$$

Instantons have been deployed to collect wind speed data every day. The portion of the wind speed profile extracted from the collected information includes pitch and unpitched zones. The data is filtered using preprocessing techniques based on the Gaussian function algorithm [Salem et al., 2022]. To make simulation easier, the data is also scaled for 48 seconds. Realistic wind speed data and the preparation process are shown in Figure 3.

The average hourly wind speed at the axis height and the power curve of the wind turbine define its hourly output, to calculate the wind turbine's output, the average hourly wind speed given in the recorded data must be converted to this height equivalent. The wind speed formula can be expressed as follows using the power function:

$$V/V_0 = (Z/Z_0)^{\emptyset} \quad (6)$$

where: V_0 is the wind speed at the reference height Z_0, $\emptyset$ is the ground surface friction coefficient, and V is the wind speed at the target height Z (m/s^2) [Modu, B., et al., 2024, Abdelshafy, 2018]. The following formula can be used to get the total power extracted (Pw) from the wind turbines at any given time:

$$P_w = \begin{cases} 0 & V<V_{cut-in}, V>V_{cut-out} \\ N_w V^3 a - P_{rate/\_w} b & V_{cut-in}<V<V_{rate} \\ N_w P_{rate/\_w} & V_{rate}<V<V_{cut-out} \end{cases} \quad (7)$$

Then using the constant a and b:

$$a = \frac{P_{rate/\_w}}{V^3{}_{rate} - V^3{}_{cut-in}}, \; b = \frac{V^3{}_{cut-in}}{V^3{}_{rate} - V^3{}_{cut-in}} \quad (8)$$

where: V is the hourly wind speed; N_w is the number of wind turbines; P_{rate_w} is the rated power (kW); and V_{cut-in}, V_{rate}, and $V_{cut-out}$ stand for the cut in, rated, and cut out wind speeds, respectively [Maleki, A., 2018].

Modeling of photovoltaic

As the mathematical model for PV cells is provided in [Molaro and Monai, 2012], the conventional power characteristic of a PV module is given in [Mekhamer, Aly S, et al., 2024]. PV arrays must be used at their highest power point to maximize power output. The high-frequency boost DC-DC converter, or MPPT device, is placed between the photovoltaic array and the DC bus. It receives DC input from the PV array, converts it to a different DC voltage, and then transfers the current to the DC bus. Figure 4 shows the C-V & P-V characteristics as well as the fitted PV module for the ZAFARANA550 W (JA Solar brand) (JAM72S30-540/MR/1500 V) [Molaro and Monai, 2012].

Modeling of fuel cell

Figure 5 depicts proton-exchange membrane fuel cells or PEMFCs. Through an electrochemical reaction with O_2, this electrochemical device transforms the chemical energy of H_2 fuel into electrical energy. Heat and water are the end products of this chemical process.

H_2 enters the PEMFC at the anode gas entry [Elnaghi, et al., 2023]. PEMFC is the best option to employ as a backup source in hybrid renewable systems due to hydrogen's high energy density. The H_2 and O_2 at the PEMFC's anode and cathode inlets can be determined using equations [Alham et al., 2023] for all chemical reactions.

- Anode reaction:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (9)$$

- Cathode function:

$$1/2\, O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (10)$$

- Overall function:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O + \text{energy (electriacl power + heat)} \quad (11)$$

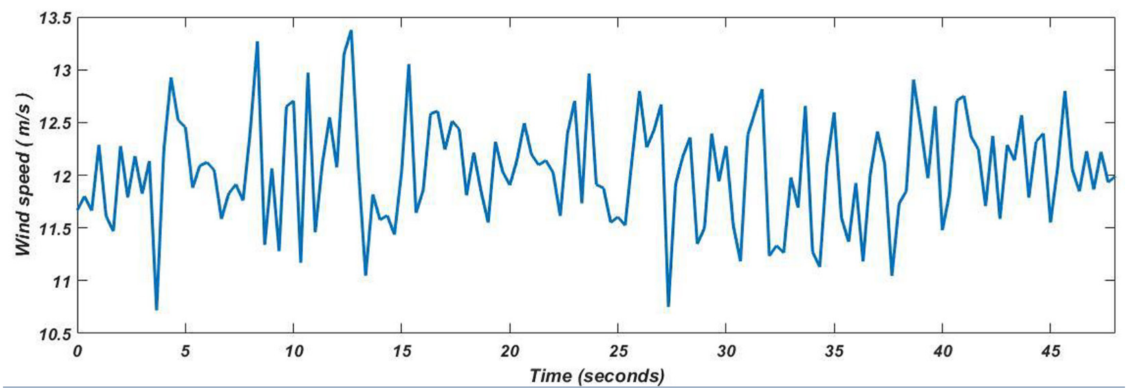


Figure 3. Wind speed recording

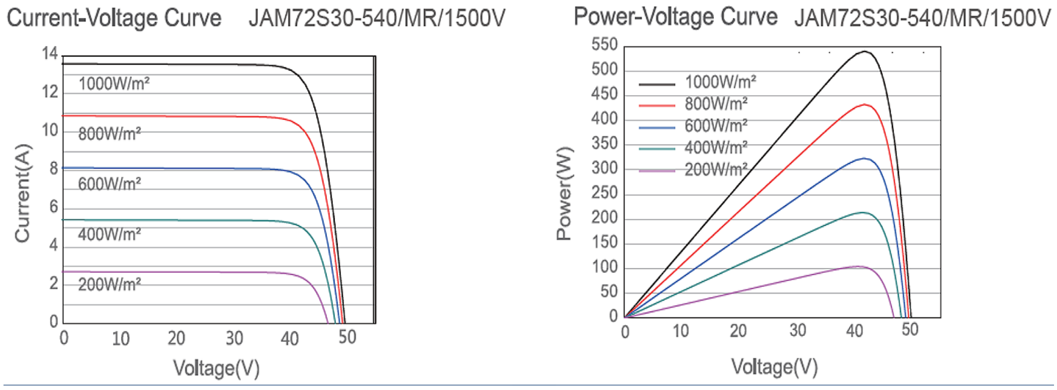


Figure 4. The installed PV module unit C-V & P-V characteristic in Zafarana [Molaro and Monai, 2012]

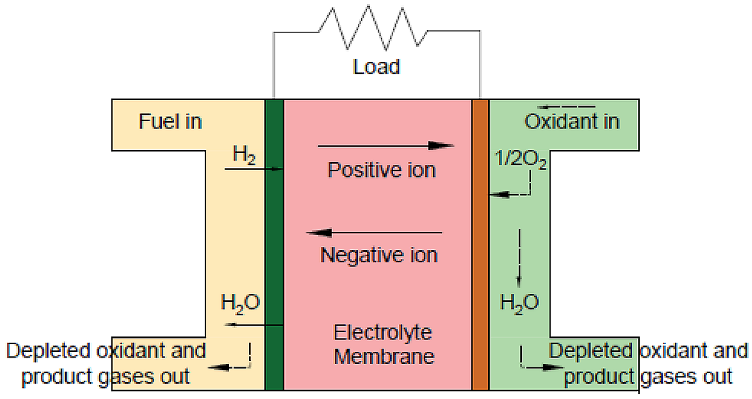


Figure 5. Schematic diagram of fuel cell (PEMFC) [Das et al., 2022]

Modeling of electrolyzer

An electrochemical unit that converts electrical energy into chemical energy is called an electrolyzer. Usually, it is employed to extract hydrogen from water, which is subsequently utilized for several applications, including PEMFC fuel.

According to the August 2021 agreement between Siemens Energy and the Egyptian Electricity Holding Company (EEHC), establishing a hydrogen-based economy in Egypt is the goal. An electrolyzer capacity of between 100 and 200 MW is anticipated for Egypt's first hydrogen-based energy facility. This is a step in the preparation process to make future planning for expansion easier.

Figure 6 shows the electrical equivalent circuit for a single-cell PEM electrolyzer. It is an excellent example of the importance of using more renewable energy sources and provides a workable way to convert excess energy into hydrogen.

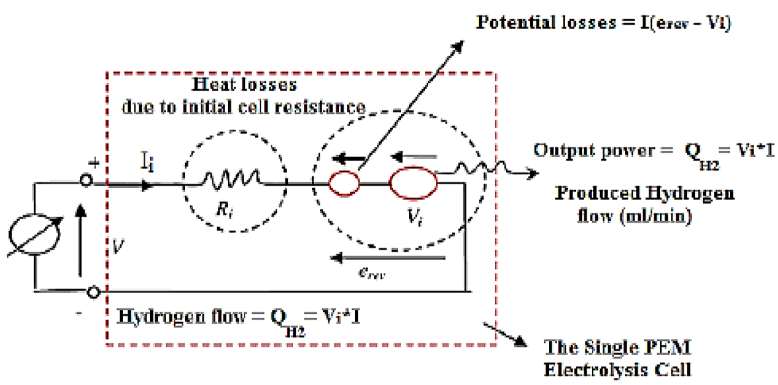


Figure 6. Equivalent circuit for single- cell PEM electrolysis [Lei, et al., 2020]

The electrolyzer consists of two electrodes and an electrolyte, just like any other electrochemical cell. An electrolysis cell's electrochemical process transforms DC electrical power into hydrogen, which is then utilized to store energy in the form of a chemical in tanks.

A sensitive, nonlinear DC load is how the electrolysis electrical circuit is depicted; an increase in applied voltage causes an increase in input current flow and H_2 productions. PEM electrolysis cells also have the benefit of being lighter and using less energy. In this work, the flow of hydrogen into a fuel cell was reversed using an electrolyzer with a maximum capacity of 208 kW. The current-voltage includes the reversible voltage, activation overvoltage, ohmic potential, and diffusion over-potential (or concentration over-potential) [Elnaghi, et al., 2023, Lei, et al., 2020].

The main objective function

The objective function in this study is getting high output EGC [Lei, et al., 2020] and minimum LPSP as follows:

$$\text{OF} = \text{EGC} + \text{LPSP} \tag{12}$$

where: LPSP is the probability of a loss of power supply and EGC is the cost of energy generation. These are detailed in the following. Weights for EGC and LPSP are possible in the objective function; nevertheless, the best result is obtained when their weights are equal.

$$\text{EGC} = \frac{\theta_{TOT}}{\sum_{t=1}^{8760} P_{load}(t)} \tag{13}$$

As θ_{invest} is assumed by this function [Khattak Sheharyar, et al., 2024]:

$$\theta_{TOT} = \theta_{Invest} + \theta_{rep} + \theta_{O\&M} + \theta_{Pen} + \theta_{Buy} - \theta_{Sell} \tag{14}$$

This parameter $\theta_{O\&M}$ will be given from Table 1 and parameter θ_{Sell} from Table 2, and θ_{invest} from the next equation

$$\theta_{Invest} = \sum_{i=1}^{N_{com}} \theta_{Invest\_\sigma} \times CRF(\text{r}, \delta_\sigma) \times \mu_\sigma \tag{15}$$

$$CRF(\text{r}, \delta_\sigma) = \frac{i(1+r)^{\delta\sigma}}{i(1+r)^{\delta\sigma}+1} \tag{16}$$

where: for component σ with an interest rate of i and a component lifespan of δ_σ, $CRF(i, \delta_\sigma)$ is the capital recover factor (CRF).In this study, the interest rate is 0.06.

$$\theta_{rep} = \frac{\delta_{syst} - \delta_\sigma}{\delta_\sigma} \theta_{rep\_\sigma} \tag{17}$$

In this case, the power system's planned lifespan, $\delta syst$, is 25 years. Table 1 has θ_{rep_σ}.

$$\theta_{Invest} = \theta_{Invest} \times \frac{-LPSP - \tau_{LPSP}}{2} \times \sum_{t=1}^{8760} P_{grid(t)} + \theta_{Pen2} \times \frac{F_{P_{sell}} - \tau_{fluc} + F_{P_{sell}} - \tau_{fluc}}{2 \times \tau_{sell}} \times 100 \tag{18}$$

where: θ_{Pen1} = 100\$/Kwhθ_{Pen2} = 50,000\$/%.τ_{LPSP}= 0.05θ_{fluc} = 0.33

$$\text{LPSP} = \frac{\sum_{t=1}^{8760} [P_{grid(t)} - P_{inv,out} - P_{wind\,(t)}]}{\sum_{t=1}^{8760} P_{grid(t)}} \tag{19}$$

$$F_{P_{sell}} = \frac{P_{sell,max}(t) - P_{sell,min}(t)}{\Delta t} \tag{20}$$

The following is the mathematical expression for the optimization limitations related to LPSP, fluctuation of power trade with the main grid, and hydrogen tank:

- LPSP ≤ τ_{LPSP}
- $F_{Psell} \leq \tau_{fluc}$
- $M_{H2,min} \leq M_{H2} \leq M_{H2,max}$

This study examines a tribrid renewable power system, and a novel proposed method called (MSOT) is used to estimate the optimal size of each component. Photovoltaic panels, wind turbines, fuel cells, electrolyzers, hydrogen tanks, rectifiers, and inverters make up this tribrid power system. To feed its 2500 MW, 120 KV local grid, the tribird system and optimization are applied to the data that is taken from Zafarana, Egypt. Achieving the lowest power generation cost while maintaining the lowest PSP is the aim of the optimization's flow chart which has been shown in Figure 7. When compared to any traditional method optimization techniques, the proposed method modified firefly algorithm (MFFA) yielded results that have been taken in this study.

Table 1. Economic information of the system components [Lei, et al., 2020]

System component	Wind turbine	Photovoltaic	Fuel cell	Inverter/ rectifier	Hydrogen storage	Electrolyzer
Investment cost θ_{invest_s} [\$/Unit]	19400	7000	3000	800	1300	2000
O&M $\theta_{O\&M}$ [\$/Unit × y]	75	20	175	10	15	25
Replacement θ_{rep} [\$/Unit]	15000	6000	2500	750	1200	1500
Lifespan d_s	20	20	5	15	20	20

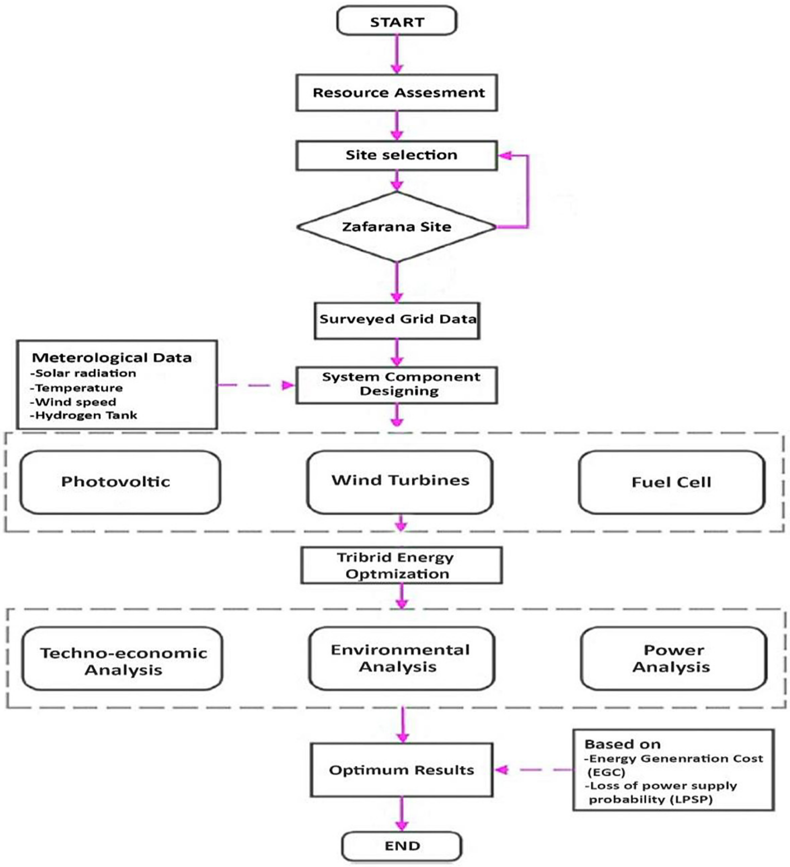


Figure 7. Flow chart of the proposed system

THE SIMULATION SETUP WITH ALGORITHMS

A comprehensive simulation was created, encompassing the tribrid system's photovoltaic and wind turbine components. The atmospheric specification parameters are displayed in Table 3. [NREA] and a fuel cell with an electrolyzer and a hydrogen tank. Figure 8 shows the Simulink model for all these systems used to serve the Egyptian electric grid and small RO plant using MATLAB/Simulink software.

Table 3. Atmospheric specification parameters [NREA]

Month	Average wind speed (m/s)	Irradiation (w/m^2)
January	5.44	656
February	6.90	671
March	4.56	702
April	6.81	691
May	6.98	729
June	8.08	808
July	8.12	806
August	9.12	793
September	8.64	758
October	7.61	689
November	5.47	679
December	5.61	672

The simulation was run under various weather conditions to illustrate the analysis and findings of the suggested tribrid system. The results that are displayed are based on the fluctuating conditions that were examined using the straightforward PI controller control approach, which is already in use in the Zafarana wind farm facility.

When optimizing the active power generation from renewable energy sources (such as photovoltaic (PV) systems, wind turbines, and fuel cells), different optimization algorithms can be employed to achieve the best results. Here's a comparison of the modified firefly algorithm (MFFA), genetic algorithm (GA) [Zafarana Wind Farms (545 MW) annual report], and particle swarm optimization (PSO) in this context, with a focus on their performance in terms of active power generation and generation cost.

The optimization process involves determining the optimal size of each system component to meet the load demand while minimizing

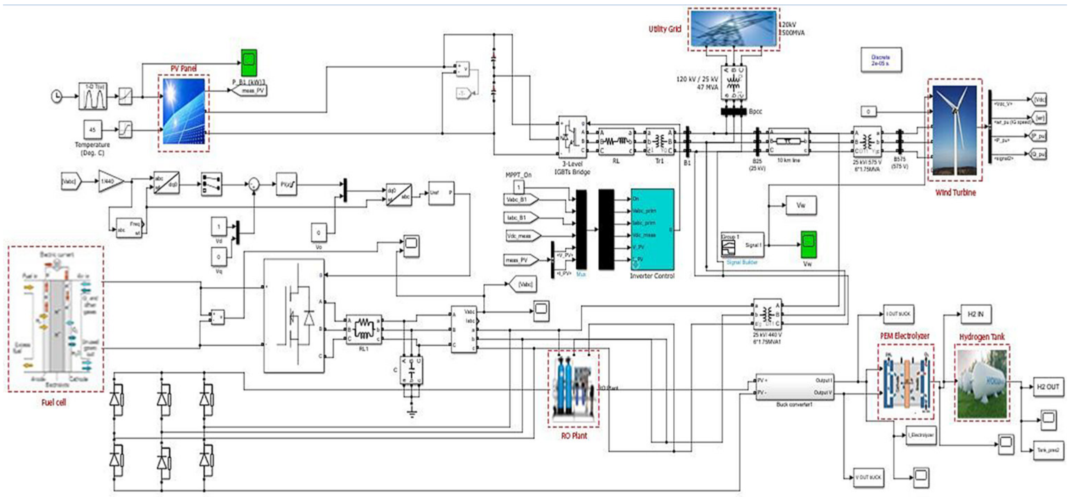


Figure 8. The proposed MATLAB/Simulink model.

costs and maximizing efficiency. Factors considered in optimization:

- Meteorological data: Solar irradiation and wind speed data are crucial inputs for predicting renewable energy generation and optimizing system design.
- Load demand: Accurately forecasting the load demand is essential for determining the required system capacity and optimizing energy storage.
- Loss of power supply probability (LPSP): LPSP is a critical reliability metric, and the optimization aims to minimize it, ensuring an uninterrupted power supply.

RESULTS

According to Figure 9 and the number of iterations to 300 that have been done between the three methods related to the energy generation cost ($/KWh), the modified firefly algorithm (MFFA) is frequently the best option for maximizing the active power generation of renewable energy sources, such as fuel cells, wind turbines, and photovoltaic systems, according to the result. It is a good fit for this work because of its benefits in managing multi-modal, complicated, and nonlinear objective functions. Because of its enhanced convergence characteristics and capacity to efficiently balance exploration and exploitation, MFFA typically performs better in optimizing active power generation and lowering generation costs than PSO and GA.

The active powers of each bus bar throughout the system are displayed in Figure 10. The actual power produced by the wind turbine, with an average of 8 MW and a transient period of 18 seconds, is displayed in Figure 10a. The genuine

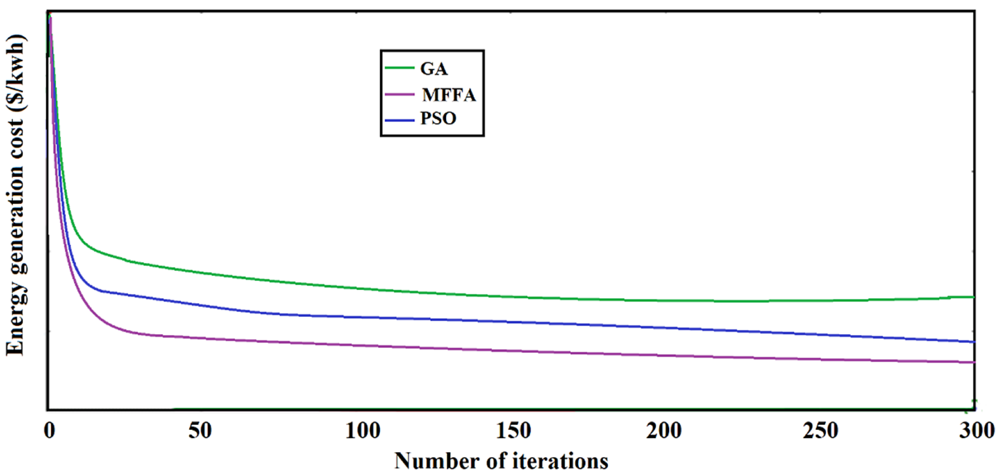
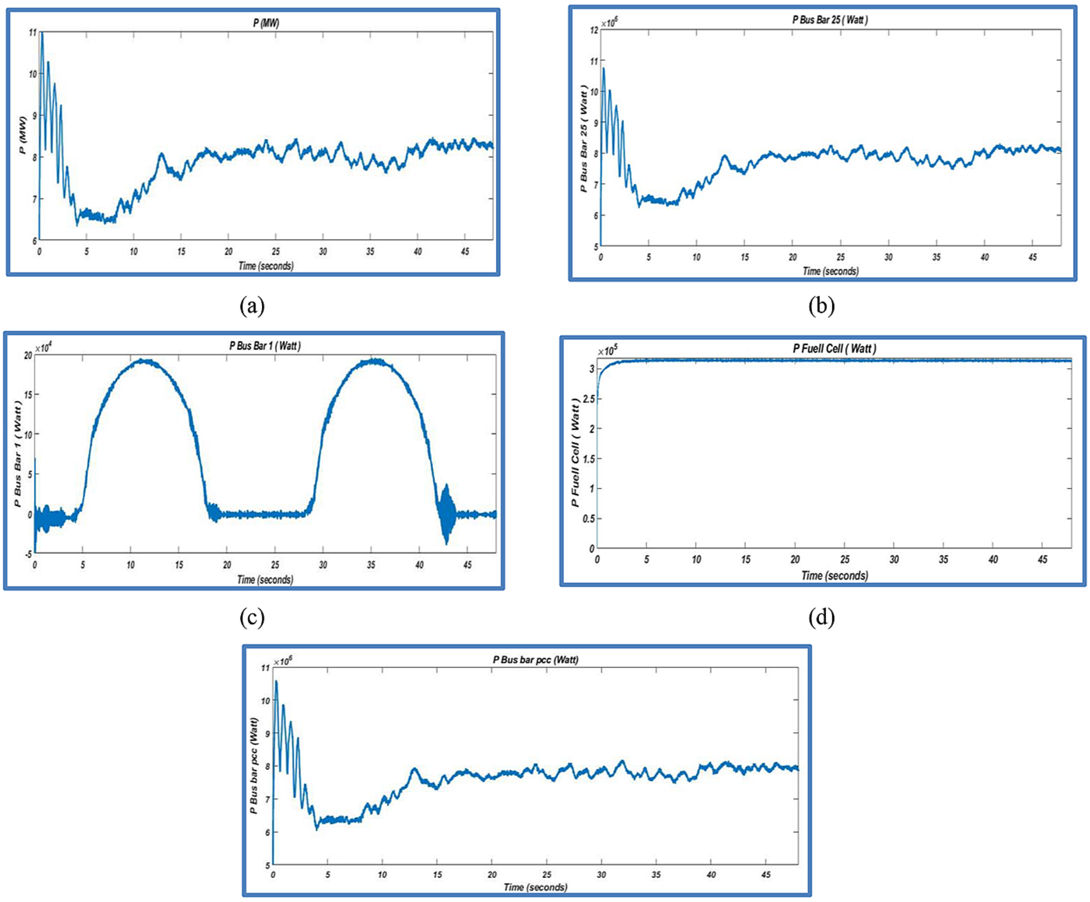


Figure 9. The convergence of the MFFA, SOA, and GA.



(a) (b) (c) (d) (e)

Figure 10. Active power of (a) wind turbine, (b) Bus Bar 25, (c) PV system, (d) fuel cell, and (e) Bus Bar PCC

power at Bus Bar 25 is displayed in Figure 10b, with an average of 8 MW and a transient period of 18 seconds. The PV system's Bus Bar 1's active power, which peaked at 190 KW, is seen in Figure 10c. The fuel cell system's active power, with an average value of 190 KW and a transient time of 5 seconds, is displayed in Figure 10d. The active power at the Bus Bar PCC is displayed in Figure 10e with a transient time of 18 seconds and an average value of 8 MW.

CONCLUSIONS

This study simulates different variations in wind speed and sun radiation using MATLAB Simulink. The results showed that the greatest alternative for the Zafarana plant is a wonderful approach to deal with several challenges that are present in the facility, including oscillations of the wind turbines and short-term power outages. Lastly, it is shown that by connecting the fuel cell, together with its electrolyzer and PV system, to the main AC bus of the PWM inverter, the stability and dependability levels of the tribrid system were raised.

Increased power output: The implementation of the tribird system has successfully increased the overall power generation capacity of the Zafarana plant, bridging the gap during periods of low output as shown in MATLAB/Simulink.

Improved load forecasting: The study has developed effective forecasting models that enhance the predictability of energy loads, ensuring optimal resource allocation and management.

Minimized power losses: The integration of these systems has led to a reduction in power losses, enhancing the overall efficiency of energy distribution.

REFERENCES

1. Abdalla, A.M., et al. (2022). Water desalination plant powered by solid oxide fuel cell technology in Egypt. *Journal of Cleaner Production*, 365, 132570.
2. Abdelshafy, A.M., Hassan, H., Jurasz, J. (2018).

Optimal design of a grid-connected desalination plant powered by renewable energy resources using a hybrid PSO–GWO approach. *Energy Conversion and Management*, 173, 331-347.

3. Abdoulaye, M.A., et al. (2024). Optimal sizing of an off-grid and grid-connected hybrid photovoltaic-wind system with battery and fuel cell storage system: A techno-economic, environmental, and social assessment. *Applied Energy*, 365, 123201.
4. Alham, M.H., Gad, M.F., Ibrahim, D.K. (2023). Potential of wind energy and economic assessment in Egypt considering optimal hub height by equilibrium optimizer. *Ain Shams Engineering Journal*, 14(1), 101816.
5. Das, H.S., et al. (2022). A comprehensive review on power conditioning units and control techniques in fuel cell hybrid systems. *Energy Reports*, 8, 14236–14258.
6. Devrim, Y., Bilir, L. (2016). Performance investigation of a wind turbine–solar photovoltaic panels–fuel cell hybrid system installed at İncek region–Ankara, Turkey. *Energy Conversion and Management*, 126, 759–766.
7. Elnaghi, B.E., Abelwhab M.N., Ismaiel A.M., Mohammed R.H (2023). Solar hydrogen variable speed control of induction motor based on chaotic billiards optimization technique. *Energies*, 16(3), 1110.
8. Egyptian Energy Transition Research Association. (2024). Retrieved August 1, 2024, from https://egyptera.org/ar/TarrifAug2024.aspx#.
9. Jahannoosh, M., et al. (2021). New hybrid meta-heuristic algorithm for reliable and cost-effective designing of photovoltaic/wind/fuel cell energy system considering load interruption probability. *Journal of Cleaner Production*, 278, 123406.
10. Khattak, S., Yousif, M., Hassan, S.U., Hassan, M., Alghamdi, T.A. (2024). Techno-economic and environmental analysis of renewable energy integration in irrigation systems: A comparative study of standalone and grid-connected PV/diesel generator systems in Khyber Pakhtunkhwa. *Heliyon*, 10(10).
11. Koholé, Y.W., et al. (2024). Optimization of an off-grid hybrid photovoltaic/wind/diesel/fuel cell system for residential applications power generation employing evolutionary algorithms. *Renewable Energy*, 224, 120131.
12. Lei, G., Song, H., Rodriguez, D. (2020). Power generation cost minimization of the grid-connected hybrid renewable energy system through optimal sizing using the modified seagull optimization technique. *Energy Reports*, 6, 3365–3376.
13. Maleki, A. (2018). Design and optimization of autonomous solar-wind-reverse osmosis desalination systems coupling battery and hydrogen energy storage by an improved bee algorithm. *Desalination*, 435, 221–234.
14. Mekhamer, A.S., et al. (2024). Coati optimization algorithm-based optimal frequency control of power systems including storage devices and electric vehicles. *Journal of Energy Storage*, 93, 112367.
15. Mekhamer, A.S., Hasanien, H.M., Alharbi, M., Tostado-Véliz, M., Jurado, F., Zaky, D.A. (2024). Coati optimization algorithm-based optimal frequency control of power systems including storage devices and electric vehicles. Journal of Energy Storage, 93, 112367.
16. Ministry of Electricity and Renewable Energy. (n.d.). Tariff of electricity report.
17. Ministry of Electricity and Renewable Energy. (n.d.). Zafarana Wind Farms (545 MW) annual report.
18. Molaro, P., Monai, S. (2012). Solar atlas revised. Astronomy & Astrophysics, 544, 125.
19. Modu, B., et al. (2024). Operational strategy and capacity optimization of standalone solar-wind-biomass-fuel cell energy system using hybrid LF-SSA algorithms. *International Journal of Hydrogen Energy*, 50, 92–106.
20. Naderipour, A., et al. (2021). Comparative evaluation of hybrid photovoltaic, wind, tidal and fuel cell clean system design for different regions with remote application considering cost. *Journal of Cleaner Production*, 283, 124207.
21. Roy, P., et al. (2022). Recent advances of wind-solar hybrid renewable energy systems for power generation: A review. IEEE Open Journal of the Industrial Electronics Society, 3, 81–104.
22. Salem, A.A., ElDesouky, A.A., Alaboudy, A.H.K. (2022). New analytical assessment for fast and complete pre-fault restoration of grid-connected FSWTs with fuzzy-logic pitch-angle controller. International Journal of Electrical Power & Energy Systems, 136, 107745.
23. Saleh, A., Awad, A., Ghanem, W. (2019). Modeling, control, and simulation of a new topology of flywheel energy storage systems in microgrids. *IEEE Access*, 7, 160363–160376.
24. Wang, Y., et al. (2024). Economic and technical analysis of an HRES (Hybrid Renewable Energy System) comprising wind, PV, and fuel cells using an improved subtraction-average-based optimizer. *Heliyon*, 10(12).
25. Wang, Z., Zhang, X., Rezazadeh, A. (2021). Hydrogen fuel and electricity generation from a new hybrid energy system based on wind and solar energies and alkaline fuel cell. *Energy Reports*, 7, 2594–2604.