An AI-based Algorithm for Energy Management of Hybrid Renewable Energy System

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Abstract—**In recent times energy demand has increased due to several factors, such as the growing world population, conventional ways of energy transmission & distribution, adopting less energy-efficient technologies, etc. These factors contribute towards more utilization of natural resources to meet the energy requirements, thus polluting the environment by producing harmful gases and increasing the energy cost. This paper addresses the aforementioned challenges, where it aims to look for more sustainable ways of energy production such as solar energy, wind energy, and biomass. This paper designed an off-grid system that aims to meet the University of Palermo's energy demand at a minimum annualized system cost. In this design, two ways are adopted for energy storage: 1) battery storage, and 2) hydrogen-based storage. The priority is to charge the batteries when excess energy is available. When the battery is fully charged and still some energy is available, this energy is used to operate the electrolyzer to produce hydrogen, which can also be used to produce again energy through fuel cells. This paper implemented an improved grey wolf optimization algorithm to find optimal power flow. The advantage of using it over other optimization algorithms is that it reduces premature convergence, and finds the global best solution. The result shows that, when the sources are not enough, the storage system can release enough energy for all time in the day.**

Index Terms—**Energy Management, Optimization, Hybrid Renewable Energy System, Hydrogen Production.**

I. INTRODUCTION

The global population has reached 8 billion [1], resulting in an increase in daily heating and energy demands and the consumption of more oil, coal, and natural resources. This excessive utilization of natural resources leads to the production of more CO_2 and NO, which strongly pollutes the atmosphere. The aim of addressing climate change drives the exploration of alternative, sustainable methods for energy production. Renewable energy sources such as solar, wind, hydro, biomass, and tidal energy are examples of such resources. Although solar photovoltaic (PV) energy conversion systems with storage systems are a considerable option for providing the energy demand [2]–[4]. The inherent limitations such as low efficiency and high cost per kilowatt-hour of energy production are major drawbacks of this system. Therefore, wind-based energy generation technology has emerged as another viable option. However, finding the optimal size and feasibility for both solar and wind energy sources is a topic of research nowadays [5]–[7]. Another critical aspect is the unpredictable nature of weather conditions makes these sources stochastic, leading to variable energy production. Hybridizing several technologies can reduce the unpredictability at the cost of system complexity [8].

Advancements in other renewable technologies including hydropower, tidal energy, and biomass can be used in conjunction with solar-wind energy systems [9]. Among these options, biomass appears to be a promising choice as it is abundant in agriculturally rich countries and can easily be converted into electricity, heat, and biofuels [10]. Biomass-based power plants can be integrated with solar and wind energy to meet the energy demands of end-users. Numerous studies have demonstrated that solar-wind-biomass power plants are a cost-effective and viable solution for electricity production [11], [12]. Additionally, the use of battery storage can also serve as a backup option to minimize intermittency and store excess energy from renewable sources [13]. Another promising solution for long-term energy storage is hydrogen storage [14], where hydrogen is produced electrochemically from water using an electrolyzer, stored in a tank, and used to generate electricity through fuel cells. Despite the major complexity of the energy system, this approach can improve the management and reliability of renewable energy sources.

In this work, a Hybrid Renewable Energy System (HRES) is taken into account where the primary energy sources are PV, wind turbine, and biomass while considering the battery and hydrogen-based storage system. Biomass will only be utilized in an emergency, when there is less energy from solar and wind. HRES must provide stable power at a minimum system cost. Many solutions have been proposed in the recent past for finding the optimal configuration of HRES. Among them, artificial intelligence-based optimization methods have proven superior in less computational time and guaranteeing the global best solution. The details of the existing work are described in more detail in the next section.

The remainder of this paper is organized as follows. Sec-

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tion II addresses challenges associated with current methods used in the recent past and the importance of the proposed method. In Section III the main characteristics of the proposed system model and operational strategy for this work are described. Section V includes the mathematical formulation of the proposed HRES followed by a description of the proposed algorithm and main parameters of the algorithm. The last section presents a discussion of some main results. Finally, the conclusion on this work is drawn and future works are explained in Section VI.

II. RELATED WORK

Extensive literature has been published on the optimal sizing of HRES utilizing conventional techniques, software/tool-based solutions, and modern AI-based methods. Conventional techniques such as the iterative method, linear programming, and trade-off method often trap in local minima and do not guarantee the optimal/best solution. The software/tool-based solutions provide black box coding, and single objective minimization, and are computationally expensive. Hence, choosing these methods for finding the optimal component size is not a viable solution. Researchers are extensively using AI-based optimization techniques because these methods provide near-optimal solutions with less computational effort.

Zhao *et al.* proposed a bi-level optimization solution for finding the optimal configuration of a PV/wind/hydrogen-based hybrid system [15]. In the upper level, hybrid methodologies including chaotic search and Particle Swarm Optimization (PSO) are implemented to find the capacity configuration of the system whereas a non-dominated sorting Genetic Algorithm (GA) is employed in the second level to minimize the multi-objective function. The proposed methodology takes few iterations to reach the final solution. In another study, a Differential Evolution (DE) method was proposed to estimate the optimal capacity size of wind/PV/micro-hydropower/biomass/biogas and the battery storage system [16]. The objective was to achieve the optimal system size at a minimal system cost. The authors validated the efficacy of the proposed methodology by comparing the results with two optimization methods such as PSO and GA. In [17], Muleta *et al.* proposed various solutions for a standalone HRES using different optimization techniques. The author compared PSO, DE, reptile search algorithm, and manta ray foraging optimization.

One study employed the Homer tool to perform techno-economic analysis on various configurations of renewable energy sources [18]. The findings illustrate that the configuration which consists of fuel cells and a wind turbine incurs maximum energy cost. While solar energy-based grid connected system offers a cheap energy solution. Harmony search algorithm is proposed for finding the optimal configuration design of standalone PV/battery, and PV/battery/diesel generator for smart building electrification [19]. Alzahrani *et al.* combined the characteristics of the Jaya algorithm and grey wolf optimization to find the optimal combination of a standalone microgrid [20]. The microgrid consists of PV, wind turbine, and battery storage systems. The combined features of the proposed algorithm outperformed other optimization methods including the Jaya algorithm, Grey Wolf Optimization (GWO), and GA in terms of less annual cost and reliability check at 0%, 1%, 2%, 3% & 5% loss of power supply.

The above-mentioned literature suggests that AI-based optimization methods such as PSO, GA, harmony search algorithm, GWO, etc, are significantly employed for capacity planning and energy management of HRES in any sector including residential, commercial, and industrial. However, these algorithms have some inherent limitations such as harmony search, GWO, and ant colony optimization offer premature convergence, GA's performance depends upon parameters tuning, and dynamic programming requires substantial memory to store the computed results. Therefore, in this study, an improved GWO is employed to find the best solution for capacity planning and optimal sizing of HRES while meeting the energy demand.

III. PROPOSED SYSTEM MODEL

This section describes the operational strategy and working principle of the proposed system. The system model, as shown in Fig. 1, consists of three primary sources: PV, wind turbine, and biomass. The battery and hydrogen-based storage systems are considered backup options. It is expected that the proposed system will optimally meet the energy demand of the University of Palermo (Italy), considering the availability of local meteorological conditions. When there is excess energy, it will be stored in batteries. If the battery is fully charged, but still has excess energy available, it can be used to produce hydrogen in the electrolyzer. Hydrogen can be stored, and later on when the sun and wind no longer provide energy, the stored hydrogen can be used to generate electricity with the fuel cell. The proposed model shows the connection of wind turbine, biomass, and load to the AC bus as they produce AC power. DC power is generated by PV power, battery storage units, and fuel cells, which are connected to the DC bus. In this case, the DC power is converted into AC power to align with the AC load.

The HRES is designed in a way that has not only been able to reduce dependency on the grid but has the capability of being self-sustainable. This system aims to address issues like energy crises and high electricity charges by providing sustainable and environmentally friendly electricity. The primary focus of this work is to determine the optimal size of HRES that can provide the energy to the whole university's campus ensuring the reliability of the system. The mathematical modeling of each component is discussed in the next section.

IV. PROBLEM FORMULATION

The objective is to minimize the Annualized System Cost (ASC) while meeting the energy demand of the university campus. The system components include solar PV, wind turbines, biomass gasifiers, battery storage, and other fuel cell-based energy components such as electrolyzers, hydrogen tanks, and fuel cells.

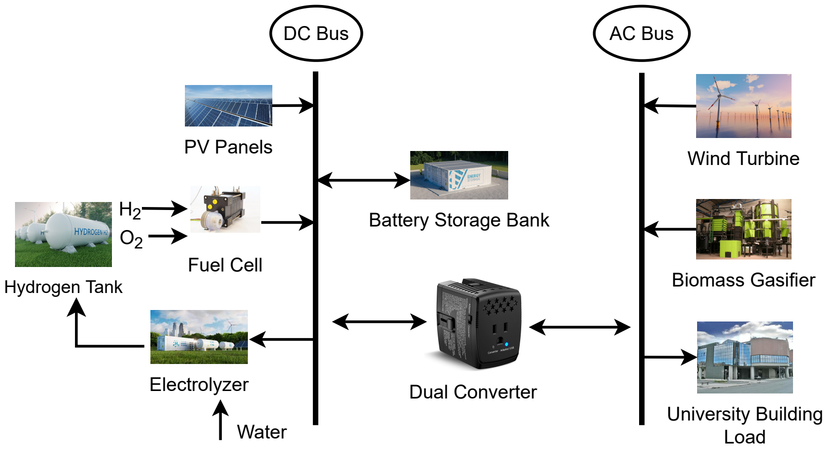

Fig. 1. Proposed system model.

A. Objective Function

The following objective function is subject to minimize considering the capacity sizing constraints,

$$Minimize\left\{Fun = N_pC_p + N_wC_w + N_bC_b + N_{hst}C_{hst} + P_gC_g\right\} \quad (1)$$

In above equation, variables N_p, N_w, N_b, and N_{hst} represent the number of PV panels, wind turbines, battery units, and hydrogen storage tank respectively. While P_g is the rating of biomass gasifier. The other variables C_p, C_w, C_b, C_{hst}, and C_g are associated with the total cost of those components.

B. Constraints

The objective function is bound to the following constraints,

$$1 \leq N_p \leq N_p^{max} \quad (2)$$

$$1 \leq N_w \leq N_w^{max} \quad (3)$$

$$1 \leq N_b \leq N_b^{max} \quad (4)$$

$$1 \leq N_{hst} \leq N_{hst}^{max} \quad (5)$$

$$1 \leq P_g \leq P_g^{max} \quad (6)$$

The above-mentioned constraints describe the size of those energy components must be within 1 and their maximum limit. N_p^{max}, N_w^{max}, N_b^{max}, N_{hst}^{max}, and P_g^{max}, show the maximum number of PV panels, wind turbines, battery storage units, hydrogen storage tank and the maximum rating of biomass gasifier.

C. Algorithm Description

The GWO is a nature-inspired meta-heuristic optimization algorithm inspired by the grey wolves' social hunting hierarchy [21]. The search or hunting process is guided by three leader wolves α, β, and γ, and the rest of the wolves ω follow the leader wolves. The leader wolves find the individual best solutions that lead the rest of the wolves to the promising areas for identifying the global best solution. The hunting process involves three main strategies: encircling the prey, hunting, and attacking.

- Encircling the prey: In this strategy, the wolves encircle the prey to initiate the hunting.
- In hunting, it is assumed that the leader wolves have the best information about the location of prey. The rest of the wolves are bound to follow the leader wolf.
- The attacking process initiates after hunting where the prey stops moving and wolves start attacking.

The hunting process led by leader wolves shows strong convergence towards these wolves. However, the algorithm suffers some challenges including lacking in population diversity, premature convergence, and imbalance between exploration & exploitation. To overcome these challenges, an improved GWO is proposed in [22] and implemented here, which uses a new search strategy based on dimension learning-based hunting associated with the selection and update steps. The algorithm has three primary phases such as initialization, movement, and lastly selection & update.

During initialization, N wolves are distributed randomly over the search space among a set of ranges $[x_i, y_j]$. It is described in equation 7.

$$P_{ij} = x_i + rand_j[0,1] \times (y_j - x_i), i \in [1, N], j \in [1, D] \quad (7)$$

The $P_i(t)$ is the vector of real values corresponding to the position of wolf i in the t-th iteration denoting as $P_i(t) = \{p_{i1}, p_{i2}, ..., p_{iD}\}$, where D represents the number of dimensions.

In the movement phase, the algorithm incorporates dimension learning-based hunting search strategy where individual wolf learn from their neighboring wolves and random chosen wolf from the population to become another candidate for the new position of $P_i(t)$. To accomplish the task, initially it calculates the distance $Rad_i(t)$ using Euclidean distance formula as described in below equation 8.

$$Rad_i(t) = ||P_i(t) - P_{i-GWO}(t+1)|| \quad (8)$$

Then, it constructs the neighbor $N_i(t)$ of $P_i(t)$ referring to $Rad_i(t)$ where D_i shows the Euclidean distance between $P_i(t)$ and $P_j(t)$.

$$N_i(t) = \{P_j(t) | D_i(P_i(t), P_j(t)) \leq Rad_i(t), P_j(t) \in P_{op}\} \tag{9}$$

Once the neighbor of $P_i(t)$ is established. The multi neighbors learning starts implementing using the random neighbor $P_{n,d}(t)$ from $N_i(t)$ and randomly selected wolf $P_{r,d}(t)$ from the population.

$$P_{i-DLH,d}(t) = P_{i,d}(t) + rand \times (P_{n,d}(t) - P_{r,d}(t)) \tag{10}$$

In the last phase, the algorithm IGWO selects the best solution by comparing fitness value of $P_{i-GWO}(t+1)$ and $P_{i-DLH}(t+1)$ as summarized in equation 11.

$$P_i(t+1) = \begin{cases} P_{i-GWO}(t+1) & if\, f(P_{i-GWO}) < f(P_{i-DLH}) \\ P_{i-DLH}(t+1) & otherwise \end{cases} \tag{11}$$

V. SIMULATIONS AND RESULTS

This section describes the characteristics of the case study and the evaluation process, followed by a detailed explanation of the simulation design and the results of the simulations performed.

The convergence curve is illustrated in Fig. 2. The algorithm runs over the period of 100 iterations and it converges around 40 iteration. The objective function is to minimize the total cost of the system. The Fig. 3 shows the energy graph for one week of July where all energy sources optimally fulfill the load demand. At the start of the week (Monday night), there is no energy from the sun, and wind produces only a small amount of energy due to wind blowing at night-time. At this time, after taking energy from a wind turbine, the rest of the energy demand is fulfilled by the battery. The battery is completely discharged to 20% until the morning time. During the daytime from 8 am to 4 pm, both solar PV and wind start producing enough energy, achieving peak production during the midday at around 1 pm and continue producing energy until the evening. For a few hours, only solar can produce more energy than the required energy demand. It means there is surplus energy available, which can be used to charge the battery. During the daytime, wind energy is also being produced. So, both PV and wind produce enough amount of energy that can easily meet the energy demand and can also be employed as a storage option in the batteries. If the battery is fully charged and still surplus energy is available, this excess energy is used to produce hydrogen and can be stored in a storage tank. In the future, hydrogen is used as a fuel for fuel cells to generate energy when a need arises.

After 4 pm, both solar and wind start producing less energy. The battery is now able to provide charge that was previously stored by using the excess energy from PV and wind. The battery can supply energy demand for the next few hours until midnight on Tuesday. After midnight or just before Tuesday morning, the battery is now completely discharged. Also due to the unavailability of the sun, no energy is generated from PV. There is a very small amount of energy available from the wind; however, it is not enough to fulfill load demand. Here comes the emergency. In such a situation, when all energy sources fail to produce energy, biomass is the only alternative. The gasifier runs to cover the remaining energy demand. As shown in Fig. 3, around 3 am to 7 am, the gasifier runs for 4 hours to meet the energy demand. In the afternoon on Tuesday, the gasifier is stopped since solar irradiance and wind speed are adequate for energy production. By using both sources, more energy can also be generated so that an electrolyzer can produce hydrogen and charge the battery while meeting the energy demand. The battery and fuel cell can produce energy during night time. This operational strategy is similar from Monday to Friday.

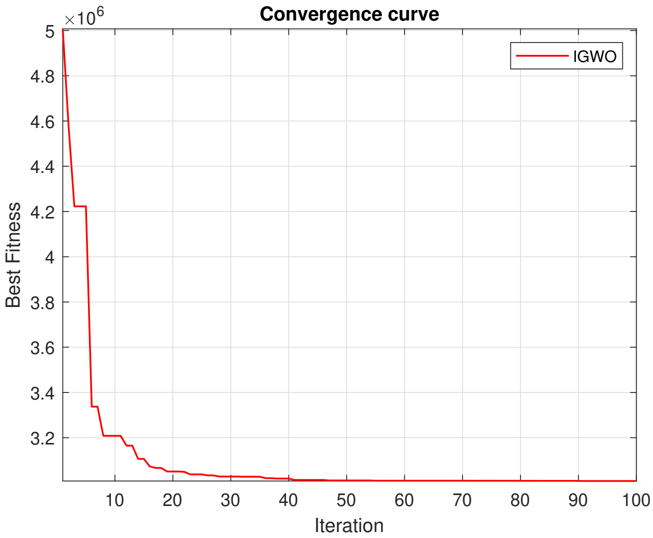

Fig. 2. Convergence curve.

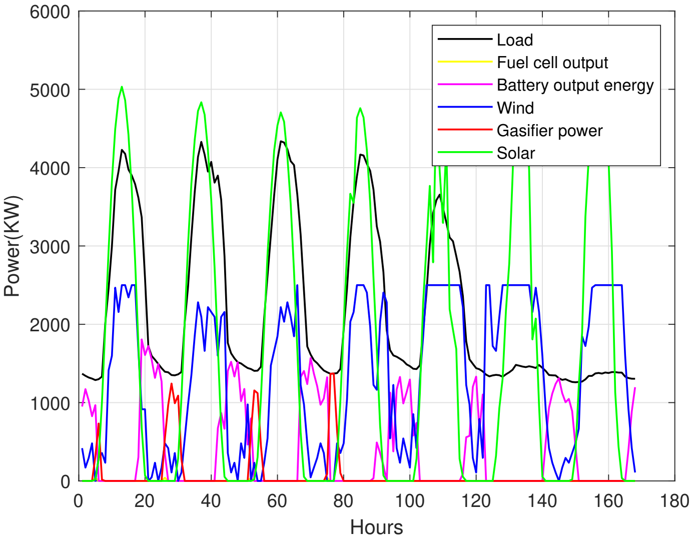

Fig. 3. Weekly power flow analysis.

During weekends, as shown in Fig. 3, less energy is required because the university remains closed most of the time. During weekends more surplus energy is available while meeting the small university load. This stored energy can charge the battery to its fullest extent. At night, when only a small amount of energy is required, the battery can provide the energy without completely discharging. Hence, no energy is required from the fuel cell and gasifier as shown in Fig. 3.
The Fig. 4 shows the state of charge representation during the whole week. Initially, it is assumed that the battery is fully charged. The battery gets fully discharged to its maximum value in the early hours of the week when there is no or little energy produced by PV and wind. During the daytime, the battery is charged to its full extent and during the night it produces energy when there is no energy from the sun or less energy is available from the wind. The curve shows charging and discharge behavior. On the other hand, the weekend is witnessing a different scenario. This is because during weekends the university's energy requirement is less and primary energy sources are enough to meet energy requirements. Hence, the major portion of the energy requirement can be fulfilled by PV and wind, and the remaining small energy requirement is taken from the battery. This is why the battery does not fully discharge.

The Fig. 5 shows energy storage in the tank and the energy coming out of it. In the daytime and during weekdays, excess energy from PV and wind is first used to charge the battery. If still some energy is available after battery charging, it employs running an electrolyzer to generate hydrogen. Hydrogen is stored as energy in hydrogen tanks. As shown in Fig. 5, during the night when no energy is available from the sun and wind, only a small amount of energy is taken from the hydrogen tank. During the day, if excess energy is present, this energy after battery charging is used to store in a hydrogen tank. Later on at night, this energy is used to match the energy demand. During the weekend, when the load requirement is less, no energy is taken from the hydrogen tank.

VI. Conclusion and Future Work

In this paper, an improved grey wolf optimization algorithm is employed to find the optimal solution to the optimization problem. It resolves the problem of the premature convergence problem and finds the global best solution. This paper designs an off-grid system that aims to optimally fulfill the energy demand of the University of Palermo (Italy) at a minimum annualized system cost. Additionally, the operational strategy performs perfectly in which the total energy demand is mainly fulfilled by PV and wind turbines. In case there is excess energy, it will be utilized to charge the batteries. Later on, when no energy is available from PV and wind, this excess stored energy is used to cover the university load demand. It is also observed that during weekdays PV and wind are not enough to provide the overall energy demand. Biomass, battery, and in a few hours fuel cell-based energy production are necessary to match the load demand. During weekends, when most of the university load is less, then a PV/wind and battery system is enough to fulfill the energy demand. The simulation of this work suggested that in order to optimally fulfill the university's load demand. The authority should install 2499.87 kW of wind turbines, 6459.30 kW of PV panels, battery storage bank should be 14999.32 kW, 1 no of hydrogen storage tank, and the gasifier size should be 1876.63 kW. The total annual cost of the system will be 3009860$/year.

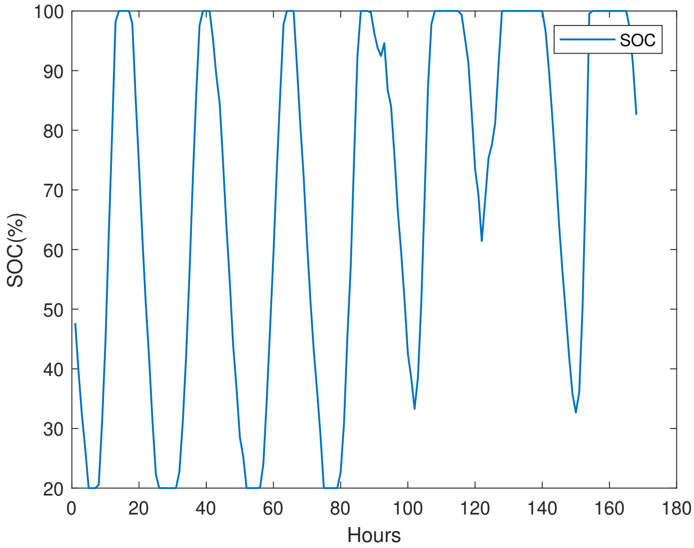

Fig. 4. State of charge weekly representation.

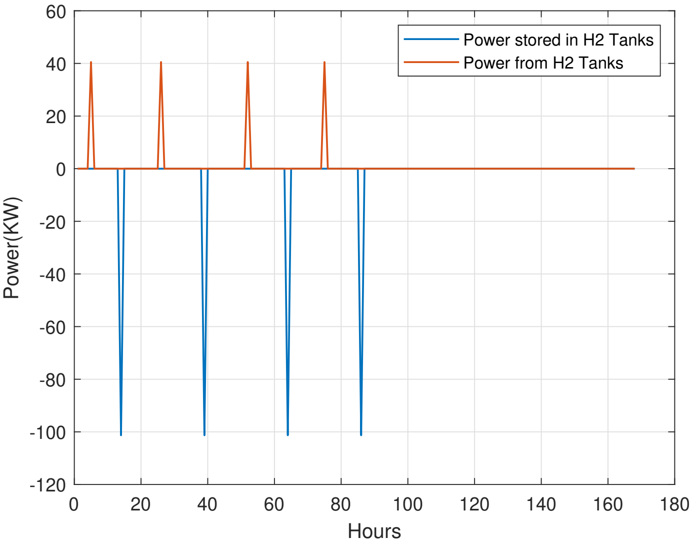

Fig. 5. Power in/out in H2 tank.

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