

Fuzzy Logic Controlled PV Microgrid for a Sports Complex in Saudi Arabia

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ABSTRACT

This paper proposes a fuzzy logic based central control facility for the isolated microgrid designed for the sports complex in a university set up in Saudi Arabia. The design aspects of the solar photo voltaic energy conversion system (PVES) for the sports complex facility are also included in the paper. Diesel generator is utilized as a backup system. The research is conducted to evaluate the effect of the proposed microgrid over the existing grid power supply in the minimization of carbon emissions and its alignment with the nation's objectives in the implementation of renewable energy-based systems in Saudi Arabia. The fuzzy logic-based system set up takes into consideration the intermittent characteristics of solar PVES output and accordingly efficiently regulate power generation, consumption and the energy storage in the sports complex. The simulation results indicate the importance and significance of the implementation of microgrid set up for major facilities in the educational institutions in Saudi Arabia.

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1. INTRODUCTION

In recent years, there has been a growing global concern regarding the impact of conventional energy systems on the environment and the urgent need to adopt sustainable alternatives [1]. The sport complex in a typical university in Saudi Arabia, serves as a hub for sports enthusiasts, athletes, and fitness enthusiasts. However, the reliance of the complex on conventional energy sources poses significant challenges in terms of energy consumption, cost, and environmental impact. To address these challenges, this paper proposes a comprehensive solution in terms of the design of a photovoltaic (PV) based microgrid with a backup system together with centralized monitoring and fuzzy control system for the sports complex.

The sport complex comprises five distinct sport facilities, each located in close proximity to one another, with a maximum distance of 800 meters separating any two facilities. This close proximity presents an opportunity to establish a centralized energy management system that can efficiently distribute and monitor the energy consumption of the entire complex. By connecting the electrical power systems of all the facilities to a single central energy management system, energy usage can be streamlined, resource allocation optimized, and thus paving the way for a sustainable future [2]. By utilizing the proposed solar PV system, the

sport complex can significantly reduce its carbon footprint, decrease reliance on non-renewable energy sources, and contribute to a more sustainable environment [3], [4].

The first part of this paper involves the design of a solar PV system to integrate into the existing power infrastructure based on the assessment of the energy requirement of the sports complex, followed by the analysis of the economical and environmental implications of the proposed transition. This is followed by the proposed fuzzy logic controller of the PVES designed for the sports complex. The effectiveness of the controller is then established through simulation results.

2. SYSTEM DESCRIPTION

The sports complex comprises five facilities as discussed in this section.

2.1. Facility No. 1 (F1): Sport Village

The electrical system of the sport village has a spacious basketball court spanning 2150 m², a sizable volleyball court covering 2344 m², a multipurpose hall spanning 612 m², a modern gym, an Olympic-sized swimming pool measuring 1250 m², a bowling alley with 12 lanes, four squash courts spanning 522 m², and a billiard center



TABLE I: LOAD DEMAND OF THE SPORTS VILLAGE

Location	Light (kW)	A/C (kW)	Others (kW)	Total (kW)
Volleyball court	120	96	5	221
Basketball court	134.4	104	5	243.4
Swimming pool	136	94.4	5	235.4
Multipurpose hall	22.4	25.8	5	53.2
Gymnasium	8.55	17.1	5	30.65
Bowling hall	3.88	17.2	5	26.08

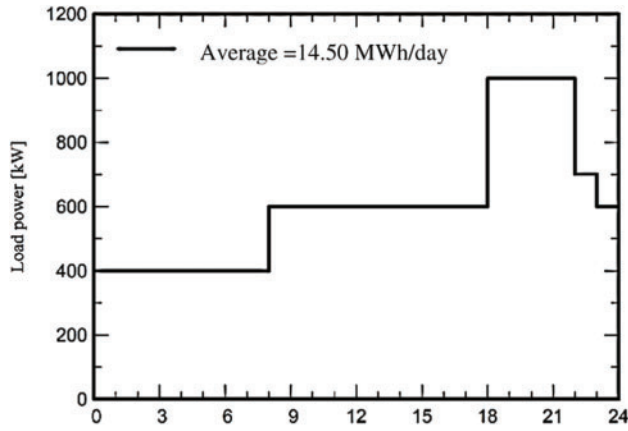


Fig. 1. Hourly load demand of the sports village over a day.

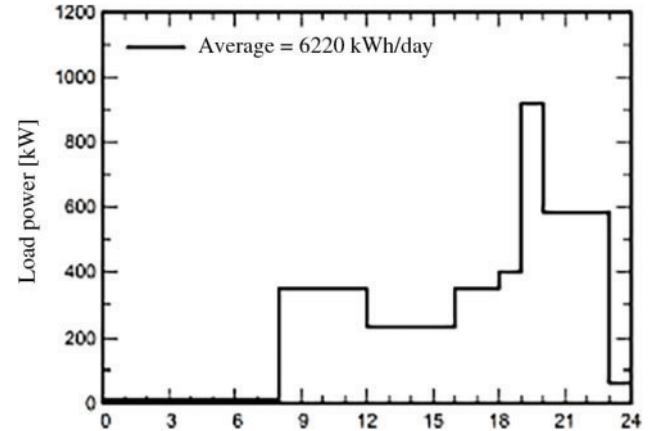


Fig. 2. Hourly load demand of the university stadium over a day.

equipped with 6 billiard tables. The facility is equipped with a physiotherapy center, a jacuzzi, a steam room, a sauna, and a modern library that has 40 computers. In addition, there are three classrooms with a capacity of up to 60 students each, as well as a spacious VIP lounge. Table I shows the energy-intensive loads consistently requiring a significant amount of power and are in high demand by users for the majority of the day. Fig. 1 shows the hourly load demand of the facility over a day.

2.2. Facility No. 2 (F2): University Stadium

The university stadium comprises two primary structures: building No. 1 and building No. 2 respectively. Building No. 1 has a combined area of 20,000 m² and houses two primary components: The main building encompassing an area of 12,000 m² and the playground spanning 8000 m². The building and playground serve as multifunctional spaces, accommodating offices, classrooms, and a variety of sports activities, including football, running, jump hurdling, and various Olympic sports. In addition, the establishment features a gymnasium, a fitness center catering to various athletic activities, and a VIP lounge. The primary electrical demand of this building, aside from the air conditioning, is the illumination of the playground. This is achieved through four lighting poles, each equipped with 64 floodlights, each having a power

rating of 2000 watts. Building No. 2 has a total area of 12,000 m². Table II shows details of the loads consistently consuming a substantial amount of energy and consistently having a high demand throughout the majority of the day. Fig. 2 shows the hourly load demand of the facility over a day.

2.3. Facility No. 3 (F3): Outdoor Fields

The outdoor fields at the university sports complex are an essential component of the campus. This facility offers students a facility for physical activity, engaging in sports, and unwinding. The fields are additionally utilized for university events, encompassing sporting competitions and concerts. Additionally, there is a single compact structure housing a small administrative office responsible for field reservations, as well as six lavatories and shower facilities. The university's outdoor fields are categorized as follows:

- Three football fields, each measuring 800 m² in area.
- Three basketball courts, each measuring 420 m² in area.
- There are four volleyball courts, each measuring 162 m² in area.
- There are three tennis courts, each measuring 680 m² in area.
- A spacious football field spanning 5346 m².

The lighting poles are distributed across the outdoor fields. Each field is equipped with two poles that support two floodlights, each with a power capacity of 1000 watts. On the other hand, the large football playground is equipped with eight poles. Every pole is equipped with three floodlights, each having a power capacity of 2000 watts. Table III

TABLE II: LOAD DEMAND OF THE UNIVERSITY STADIUM

Location	Lighting (kW)	A/C (kW)	Others (kW)	Total (kW)
Building no. 1	10	80	10	100
Playground	512	0	10	522
Building no. 2	15	80	10	105

TABLE III: LOAD DEMAND OF THE OUTDOOR FIELDS

Location	Light (kW)	A/C (kW)	Others (kW)	Total (kW)
Building	2	8	2	12
Large playground	48	0	2	50
Basketball fields	12	0	0	12
Volleyball fields	16	0	0	16
Tennis fields	12	0	0	12
Football fields	12	0	0	12

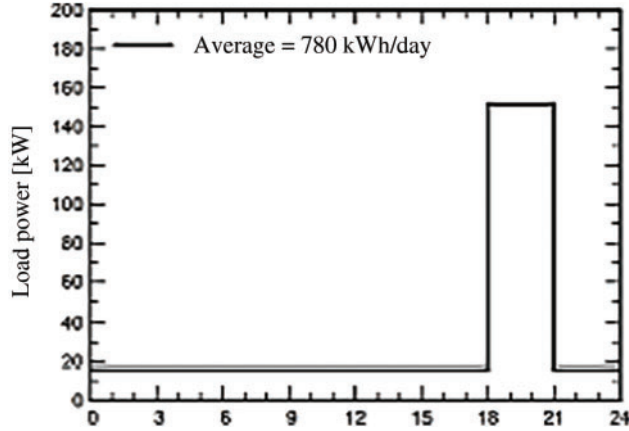


Fig. 3. Hourly load demand of the outdoor fields over a day.

TABLE IV: LOAD DEMAND OF THE HORSE CLUB

Location	Light (kW)	A/C (kW)	Others (kW)	Total (kW)
The building	2	13.5	2.5	18
Horses field lights	150	0	0	150
Horses room A/C	0	42	0	42

and Fig. 3 shows the major energy-consuming loads having a significant impact on energy usage and are in high demand from the user for the majority of the day.

2.4. Facility No. 4 (F4): Horses Club

The Horses Club which is also called Equestrian Club is a gathering place on the university campus for students, faculty, and individuals interested in equestrian activities to engage in the realm of horsemanship. Furthermore, it provides a unique and distinguished platform with a rich and prestigious past, in addition to its dedication to achieving excellence in equestrian pursuits. The club not only promotes a feeling of belongingness, but also offers a wide range of activities aimed at enhancing equestrian skills.

During the competitions, the club offers two VIP rooms for guests, along with three equestrian fields and twelve horse stable, all of which are equipped with air conditioning units.

Table IV shows the loads consuming a substantial amount of energy and consistently have a high demand throughout the day. Fig. 4 shows the hourly variation of the load demand of the Horse club over a day.

2.5. Facility No. 5 (F5): Rovers Club

The Rovers Club is an exhilarating and dynamic organization that unites individuals with a shared passion for

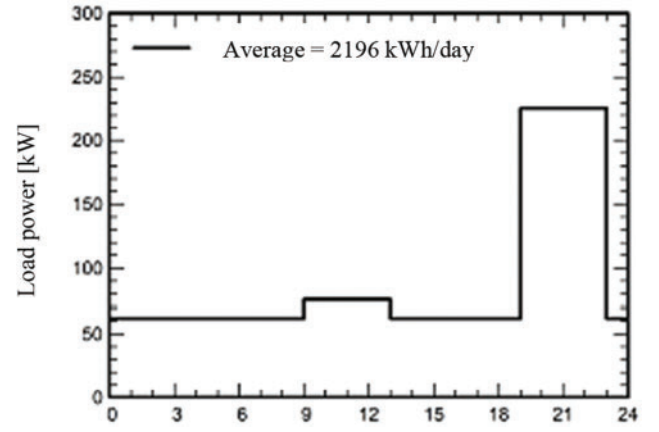


Fig. 4. Hourly load demand of the Horse club over a day.

TABLE V: LOAD DEMAND OF THE ROVERS CLUB

Location	Light (kW)	A/C (kW)	Others (kW)	Total (kW)
Building	4.4	55	0.6	60
Field lights	42	0	0	42

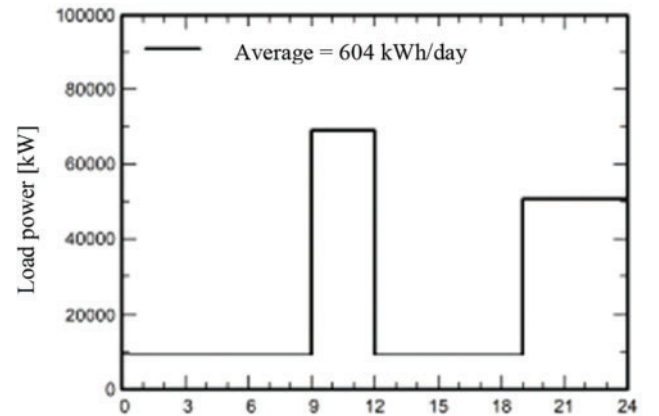


Fig. 5. Hourly load demand of the Rovers club over a day.

outdoor exploration and adventure. The primary objective of this club is to establish a platform where like-minded individuals can engage in a wide range of activities that foster personal growth, cooperation, and a deep affinity for the environment. The Rovers Club offers its members a diverse range of activities that they can select to test and motivate themselves. There are four distinct restrooms at this location. A spacious and versatile room suitable for various activities. There is a room designated for administrative purposes. Table V shows the loads consuming a substantial amount of energy and consistently have a high demand throughout the day. Fig. 5 shows the hourly variation of the load demand of the Rovers club over a day.

3. PROPOSED MICROGRID

3.1. System Description

The university can achieve energy self-sufficiency, reduce emissions, by adopting solar energy as a clean and renewable alternative to conventional power systems. [5]–[7]. A microgrid comprising a photovoltaic (PV) system, two different battery energy storage systems (BESS),

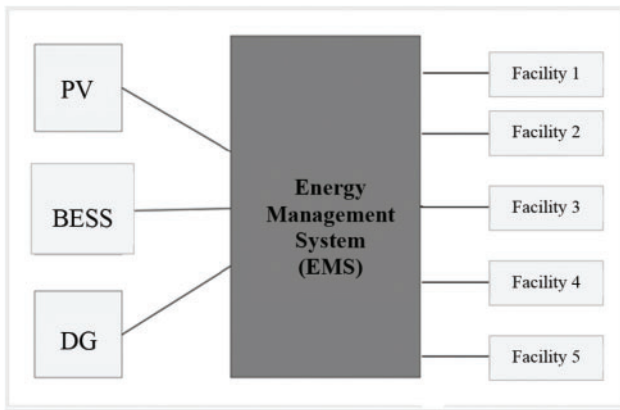


Fig. 6. Central energy management system.

and diesel generators has significant potential to fulfill the energy requirements of the sports complex. In order to ensure the effective and ideal functioning of the microgrid, a central control facility is proposed at the same site as the PV system as shown in Fig. 6.

- A 5242 kWp photovoltaic solar system is linked to a DC/DC boost converter to convert the variable output voltage of the PVES into the constant rated voltage supply required for the microgrid. The design aspects of the PVES system are given in the following subsection. The converter is equipped with a maximum power point tracker (MPPT) to optimize the harvesting of power from the PV system, regardless of fluctuations in solar irradiance.
- One diesel generator (DG) which is already existing in the sports complex with a power output of 2 MW is linked to the system.
- The microgrid also includes two different types of battery energy storage systems (BESS) with a capacity of 24276 Ah. The battery types [8] and design are given in the following sections.

3.2. PV System Design

The photovoltaic (PV) system is designed to meet the entire energy demand of the sports complex. The new facility can be located in the neighborhood of the centralized control center, offering a strategic advantage to the system. It will be equidistant from the five sports facilities, with no distance exceeding 800 m. Fig. 7 shows the location of the proposed Sport Complex Control Center.

The primary factors to be taken into account when designing a photovoltaic (PV) system [9] are solar irradiance, array orientation and tilt angle, and panel efficiency.

3.2.1. Solar Irradiance

The region of Saudi Arabia in which the university is located receives abundant solar irradiation consistently throughout the year. Limited cloud cover and a decreased likelihood of atmospheric interference over a significantly long period throughout the year, there is a good possibility for facilitating the optimal capture of solar energy. The mean yearly solar irradiance in the region varies between approximately 2100 to 2300 kWh/m², rendering it a highly

favorable site for the implementation of photovoltaic (PV) systems [10].

3.2.2. Array Orientation and Tilt Angle

Considering the latitude of approximately 21.5 degrees north in the western region, it is advisable to set the tilt angle of fixed PV systems close to this latitude as per general guidelines. Although a tilt angle of approximately 21 to 22 degrees is commonly suggested, the ideal tilt angle may differ based on specific project objectives, such as maximizing energy generation during periods of high demand or optimizing the overall annual energy output [11].

A tilt angle of 24 degrees was selected in this particular case, to maintain a consistent tilt throughout the year. Fig. 8 shows the panel's tilt angle of 24 degrees, the sun angle variations over a 24-hour period, and the panel's orientation, which provides a clear representation of how the panel's positioning aligns with the sun's movement to optimize solar energy capture. A tilt angle of 24 degrees, although not universally optimal for all seasons, is slightly steeper than the latitude of the western region. This inclination, even though slightly steeper than the latitude, facilitates the capture of additional sunlight during the winter months, when the sun is positioned lower in the sky. The inclination angle can also yield advantages during other seasons by equalizing the energy production over the course of the year. A fixed tilt system can offer a reliable and consistent energy production throughout the year, particularly if the energy demand is steady [12].

3.2.3. Panel Efficiency

The PV module chosen for the design is 445 Wp Monocrystalline Photovoltaic Module-144 half-cut [13], [14]. The module name refers to a specific type of solar panel that utilizes monocrystalline silicon cells and incorporates 144 half-cut cells. Half-cut cells are smaller cells that divided into two halves, resulting in decreased energy losses and enhanced overall performance. This design enhances shade tolerance and reduces resistive losses within the panel by enabling independent operation of each half as shown in Fig. 9. The estimation of electricity generation, demand, and losses by this panel is illustrated in Fig. 10, providing insights into its overall performance and efficiency in the system.

3.3. Battery Energy Storage System

To effectively fulfill the energy requirements of this system, which has a daily demand to the tune of 24.4 MWh, with 33% of it being utilized for air conditioning, the PV system is proposed to be incorporated with a 10 MWh battery energy storage system. The combined system will comprise two types of BESS: Lithium-ion [15] and an advanced sand battery designed to store thermal energy [16].

- The Lithium-ion battery will effectively manage the total energy storage and discharge needs. It will offer dependable energy storage capabilities, enabling efficient utilization and control of the system's power output.
- The sand battery utilizes the unique properties of sand to efficiently store and release thermal energy.

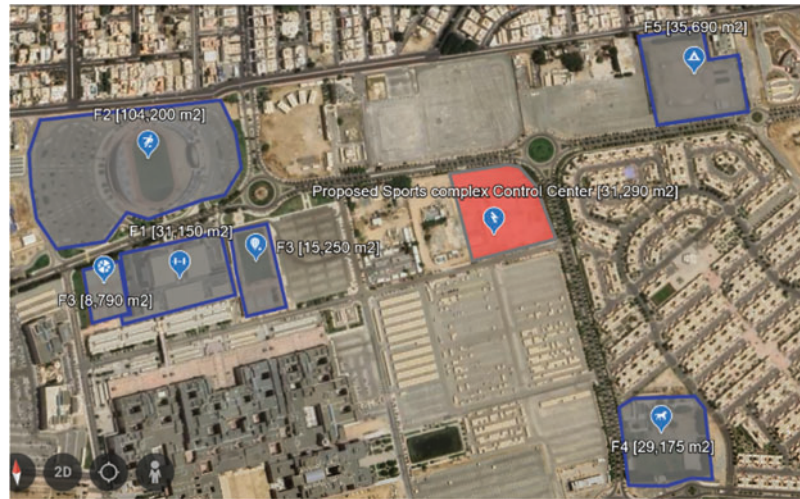


Fig. 7. Helicopter view of the control center among the facilities.

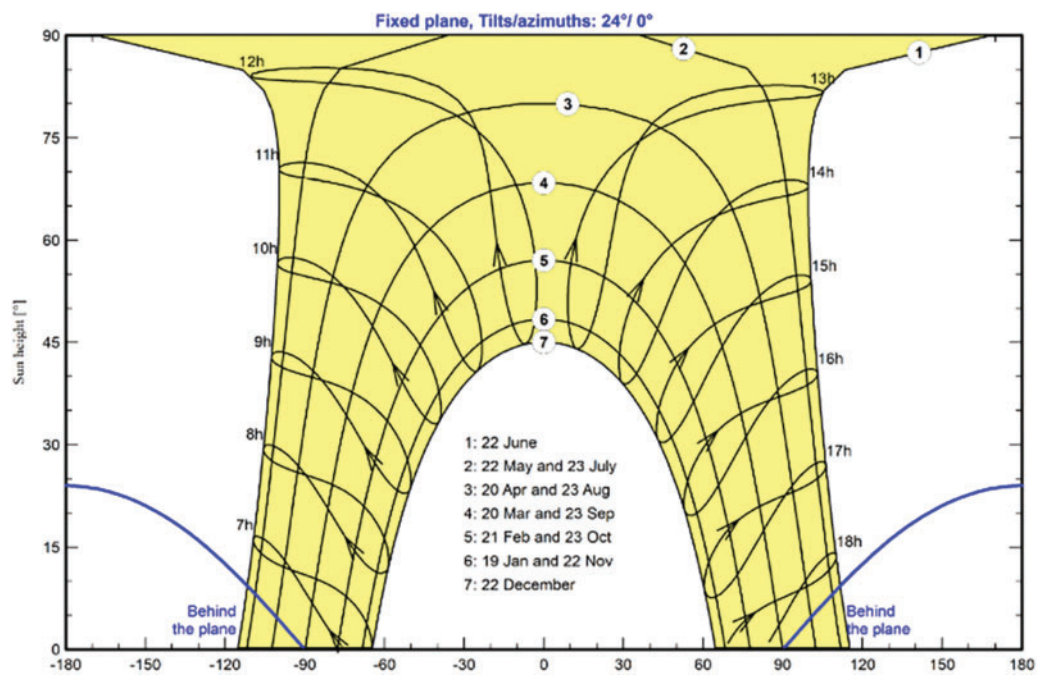


Fig. 8. Array orientation and tilt angle.

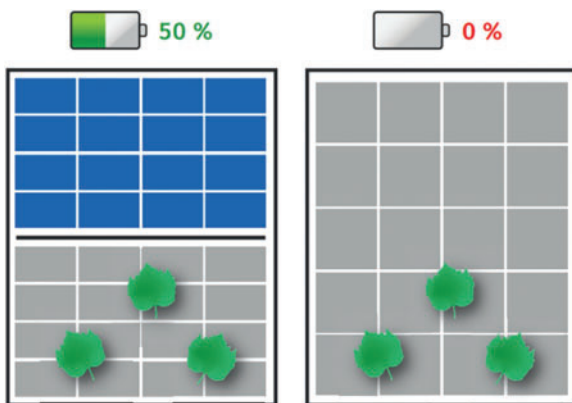


Fig. 9. Half-cut monocrystalline silicon cells vs. conventional PV cells.

This system employs a one- or two-tank configuration filled with thermally conductive sand,

functioning on the principle of thermal energy storage.

By integrating these two energy storage technologies, it can enhance the system's ability to manage energy, guaranteeing a dependable power supply for both overall energy needs and the specific cooling requirements of the air conditioning loads. The combined BESS system is a comprehensive solution that utilizes both traditional and advanced battery technologies to fulfill the various energy requirements of the system. It also incorporates the latest advancements in thermal energy storage.

Table VI shows the details of the proposed PV system designed for the sports complex using the PVSyst.

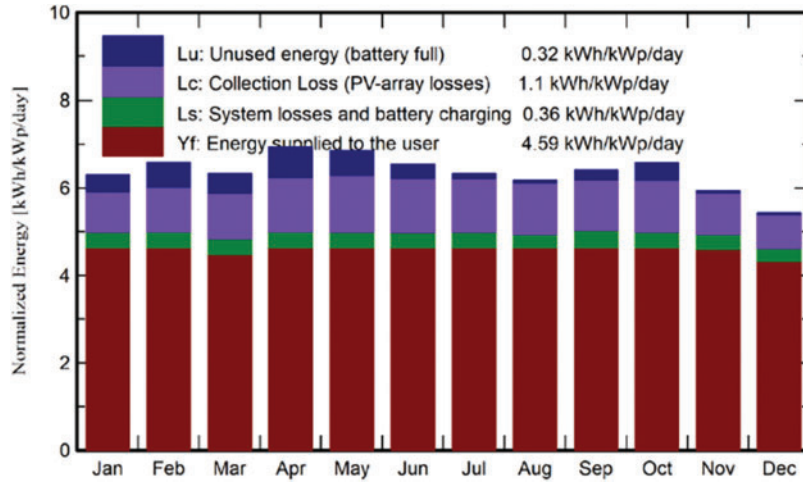


Fig. 10. Estimation of electricity generation, demand and losses.

TABLE VI: DETAILS OF THE PV SYSTEM FOR THE SPORTS COMPLEX

System parameter	Value
Load demand (MWh/day)	24.3
System power (kWp)	5242
No. of PV module (Unit)	11914
PV Module area (m2)	26508
BESS Capacity (Ah)	24276
Unused energy (kWh/year)	603452
Inverter capacity (MWh)	30

4. PROPOSED FUZZY LOGIC BASED ENERGY MANAGEMENT SYSTEM

The proposed fuzzy logic-based energy management system (FLEMS) is to ensure that the power needs are met by utilizing the solar PV system to the fullest extent possible, while also accommodating fluctuations in load demand. EMS utilizes Battery Energy Storage Systems (BESS) to store excess energy obtained from the solar PV system. This stored energy is then utilized during periods whenever the solar PV system is unable to generate sufficient power. When the solar PV system and the Battery Energy Storage System (BESS) are insufficient to meet the load demand, the Energy Management System (EMS) regulates the operation of the diesel generators to make up for the lack of solar photovoltaic (PV) energy and the BESS. FLC is employed to regulate the functioning of the diesel generators by utilizing control switches to offset the lack of renewable energy generation and the battery energy storage system [17]. The control system also regulates the State of Charge (SOC) of the Battery Energy Storage System (BESS), ensuring that it remains within the range of 20% to 95% in order to optimize its lifespan.

The fuzzy logic controller has two inputs which are the SOC of the BESS and the net power. Net power is the difference between power generated from solar panels and the load demand calculated as:

$$P_{net} = P_{solar} - P_{load} \quad (1)$$

where P_{net} represents the net power, P_{solar} represents the power generated from solar panels and P_{load} represents

the load demand power. BESS SOC is that of the sum of the Lithiumion battery and Sand battery:

$$SOC = SOC_{Sand\ battery} + SOC_{Lithium-ion\ battery} \quad (2)$$

Figs. 11–13 show the membership functions for inputs and output of the FLC. Fig. 14 shows the control surface of the fuzzy logic controller, it presents all inputs and their relationship with the generator output.

The fuzzy logic controller (FLC) rules were developed based on expert knowledge of the system's dynamic behavior, using linguistic variables to represent key inputs and outputs, and structured into a set of IF-THEN rules that reflect logical relationships between operating conditions and control actions; additionally, the membership functions were designed to be non-uniform to accurately capture the nonlinear characteristics of the input and output variables.

It shows that as demand increases, the generator's contribution rises, while the battery charging rate decreases. In order to capture the non-linear fuzzy variations in load demand and solar PV output in a more refined way, the non-uniformly distributed membership functions with more fuzzy subsets clustered in the region of more such expected variations, as shown in Figs. 11–13, is utilized. Table VII shows the rule base of the FLC.

The abbreviations LL, L, M, H, HH stand for: very low, low, low medium, high medium and high respectively and the abbreviations N4, N3, N2, N1, Z and P stand for: high negative, medium negative, small negative, very small negative, zero and positive respectively.

5. ECONOMIC AND ENVIRONMENTAL IMPACT

5.1. Economic Impact

The integration of a photovoltaic (PV) system with a Battery Energy Storage System (BESS) offers a sustainable energy solution for large-scale facilities, such as sports complexes. In this case, the system is designed to meet a daily load demand of 24.3 MWh, with a total power capacity of 5242 kWp, comprising 11,914 PV modules spread over an area of 26,508 m². The BESS has a capacity of 24,276 MWh, supported by an inverter

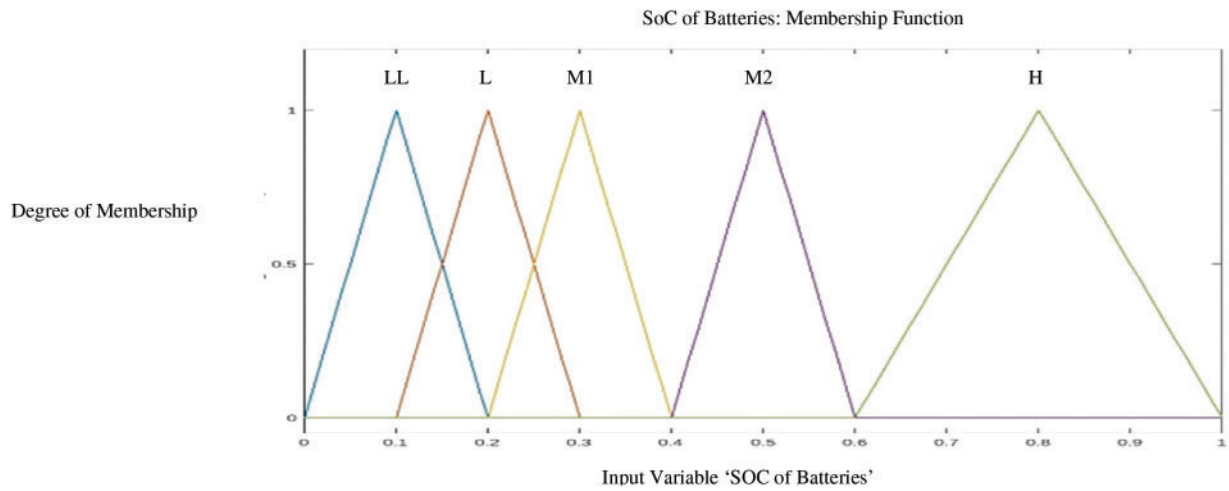


Fig. 11. Membership functions for SOC batteries.



Fig. 12. Membership functions for Net power.

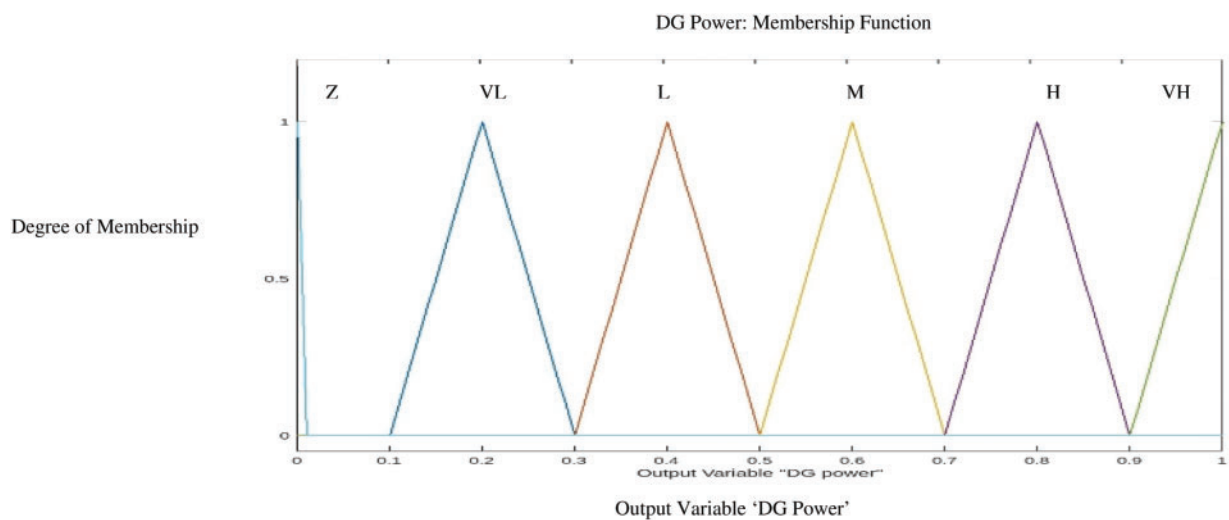


Fig. 13. Membership functions for DG power.

capacity of 30 MWh, ensuring efficient energy storage and distribution.

This section investigates the installation costs and pay-back periods under two scenarios: without government

support and with government support, as well as with the potential for selling excess energy to the national grid.

The overall installation cost of the PV system combined with the BESS is influenced by several factors, including the cost of PV modules, inverters, balance of system

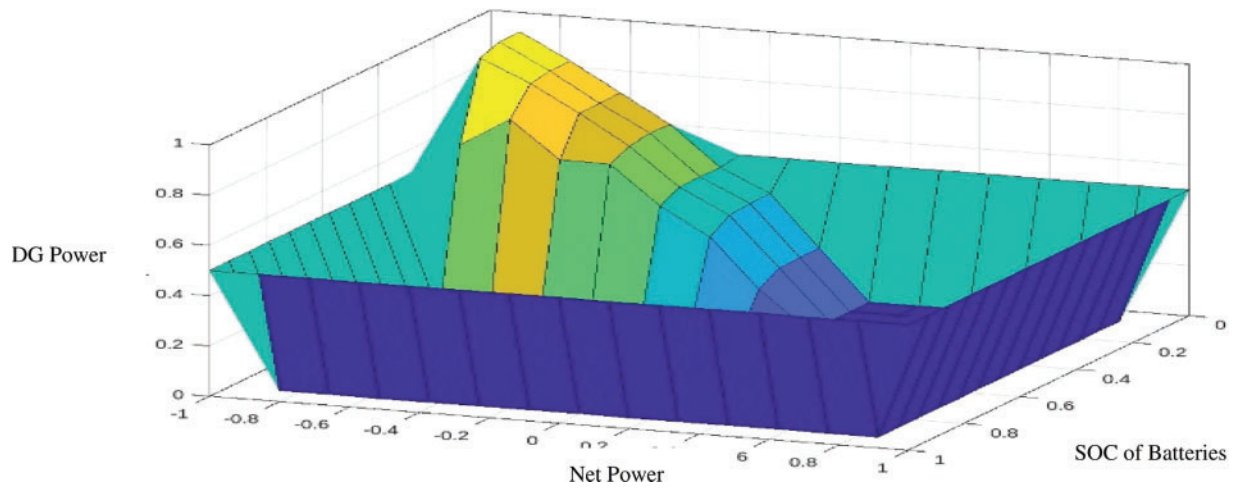


Fig. 14. Control surface of the fuzzy logic controller.

TABLE VII: RULE BASE OF THE PROPOSED FUZZY LOGIC CONTROLLER

Diesel generator		Net power					
		N4	N3	N2	N1	Z	P
SOC of BESS	LL	VH	H	M	L	VL	Z
	L	VH	H	M	L	VL	Z
	M1	Z	Z	Z	Z	Z	Z
	M2	Z	Z	Z	Z	Z	Z
	H	Z	Z	Z	Z	Z	Z

(BOS) components, labor, and the BESS itself. For utility-scale PV systems in Saudi Arabia, the installation cost is estimated between \$900 and \$1200 per kWp. In the case of a 5242 kWp system, this results in an estimated PV installation cost ranging from \$4.7 million to \$6.3 million (17.6 million to 23.6 million SAR). The BESS installation cost, based on a capacity of 24,276 MWh, typically ranges between \$300 and \$500 per kWh, leading to an estimated cost between \$7.3 million and \$12.1 million (27.4 million to 45.4 million SAR). Therefore, the total installation cost of the integrated PV and BESS system is projected to be between 45 million and 69 million SAR (\$12 million to \$18.4 million).

5.1.1. Scenario 1: Without Government Support

In the absence of government incentives or financial support, the payback period is solely determined by the system's ability to reduce electricity costs. In Saudi Arabia, the commercial electricity tariff is currently 0.20 SAR/kWh. Given the system's expected annual energy production of approximately 8869 MWh, the first-year savings would be around 1.77 million SAR. Additionally, assuming an average annual inflation rate of 2% in electricity tariffs, the system's financial savings would grow over time. For example, in the second year, the savings would increase to 1.81 million SAR, and this growth would continue throughout the system's lifespan. Over a period of 30 years, the cumulative savings, accounting for inflation, are projected to reach 70.7 million SAR. Without any government subsidies, the payback period is estimated to *range between 19 and 27 years*, depending on the final installation costs. Although the payback period may appear lengthy,

it is important to consider that the system provides long-term financial stability by mitigating the effects of rising electricity costs and contributing to sustainability.

5.1.2. Scenario 2: With Government Support

With government support, such as subsidies, tax credits, or other incentives aimed at promoting renewable energy projects in alignment with Saudi Arabia's Vision 2030, the payback period could be significantly reduced. Assuming government support reduces the installation costs by 20%–30%, the total cost would decrease to 31.5 million to 55.2 million SAR. In this scenario, the inflation-adjusted annual savings of 1.77 million SAR would result in a reduced payback period of 14 to 23 years.

Government incentives could include financial support for renewable energy infrastructure, preferential tariffs, or tax exemptions, all of which would enhance the financial feasibility of the project. The combination of lower installation costs and continued inflation-adjusted savings would accelerate the return on investment, making the project more financially attractive.

Potential for Selling Excess Energy to the SEC Grid: In both scenarios, the financial attractiveness of the project could be further enhanced by exploring the possibility of selling excess energy back to the Saudi Electricity Company (SEC) grid. The development of a feed-in tariff mechanism would allow the project to export surplus energy generated during periods of high solar power production, providing an additional revenue stream. This would ensure that no excess energy is wasted and could further reduce the payback period by generating additional income from electricity sales.

Thus, it can be seen that the payback period for the PV and BESS system without government support is estimated to range between 19 and 27 years, depending on installation costs and the inflation rate of electricity tariffs. With government support, the payback period could be reduced to 14 to 23 years, improving the financial attractiveness of the system. Moreover, by developing a mechanism to sell excess energy back to the SEC grid, the project could generate additional revenue, further shortening the payback period and enhancing the overall financial viability of the system. In both cases, the PV and BESS system offers long-term stability, energy independence, and environmental benefits, aligning with Saudi Arabia's renewable energy goals as part of Vision 2030.

5.2. Environmental Impact

The growing concerns about climate change and environmental degradation have heightened the global drive for sustainable energy solutions [18].

Once the total kWh generation is known, the total emission forms a power source can be calculated knowing the emission factor of the respective power generating system. The emission factor for grid and the solar PV systems in Saudi Arabia is 0.5059 kg CO₂ per kWh, and solar PV system is 0.04 kg CO₂ per kWh respectively. Accordingly, for a power generation of 24,300 kWh, a reduction of 11321.37 kg (92%) CO₂ can be achieved through the implementation of the proposed PV system.

The integration of a fuzzy logic-controlled microgrid can lead to further significant reductions in carbon emissions

through several mechanisms. Firstly, the optimization of renewable energy utilization is achieved through the continuous monitoring and adjustment of the energy sources by the fuzzy logic controllers. By prioritizing the use of clean energy over fossil fuels, the microgrid minimizes the carbon emissions associated with electricity generation. Secondly, the FLCs enhance the efficiency of energy conversion and storage processes within the microgrid, reducing energy losses and optimizing the use of stored energy. This results in the system requiring less energy from carbon-intensive sources, further lowering emissions. Thirdly, the FLCs can implement demand response strategies, adjusting energy consumption patterns based on availability and cost. This flexibility reduces the reliance on carbon-intensive peaking power plants and promotes the use of renewable energy during periods of high demand. The potential benefits of a fuzzy logic-controlled microgrid in reducing carbon emissions have been demonstrated in various studies [19]–[22].

6. SIMULATION RESULTS

The effectiveness of the fuzzy logic-controlled microgrid in regulating the power output of the diesel generator depending on the variations in the solar PV output and also in maintaining the charge level of the BESS within the specified limits is evaluated through system simulation corresponding to various system operating conditions on certain typical days over an year. The reduction in the

TABLE VIII: SOC SIMULATION OF THE SPORT COMPLEX FOR 24/7

Months	0 H	1 H	2 H	3 H	4 H	5 H	6 H	7 H	8 H	9 H	10 H	11 H
Jan	0.72	0.72	0.71	0.71	0.7	0.7	0.69	0.69	0.69	0.71	0.72	0.74
Feb	0.83	0.83	0.83	0.82	0.82	0.81	0.81	0.81	0.81	0.82	0.84	0.86
Mar	0.74	0.73	0.73	0.72	0.72	0.72	0.71	0.71	0.72	0.73	0.74	0.76
Apr	0.83	0.83	0.83	0.82	0.82	0.81	0.81	0.81	0.82	0.83	0.85	0.87
May	0.84	0.83	0.83	0.82	0.82	0.81	0.81	0.81	0.82	0.83	0.85	0.87
Jun	0.84	0.83	0.83	0.82	0.82	0.81	0.81	0.81	0.82	0.83	0.85	0.87
Jul	0.82	0.81	0.81	0.8	0.8	0.79	0.79	0.79	0.8	0.81	0.82	0.84
Aug	0.71	0.71	0.7	0.7	0.69	0.69	0.68	0.69	0.69	0.7	0.72	0.73
Sep	0.61	0.61	0.61	0.6	0.6	0.59	0.59	0.59	0.6	0.61	0.63	0.65
Oct	0.81	0.81	0.8	0.8	0.8	0.79	0.79	0.79	0.8	0.81	0.83	0.85
Nov	0.73	0.72	0.72	0.71	0.71	0.7	0.7	0.7	0.71	0.72	0.74	0.76
Dec	0.43	0.43	0.42	0.42	0.41	0.41	0.4	0.4	0.41	0.42	0.43	0.45
Year	0.74	0.74	0.73	0.73	0.72	0.72	0.72	0.72	0.72	0.73	0.75	0.77
Months	12 H	13 H	14 H	15 H	16 H	17 H	18 H	19 H	20 H	21 H	22 H	23 H
Jan	0.77	0.79	0.81	0.82	0.83	0.82	0.81	0.79	0.77	0.75	0.74	0.73
Feb	0.88	0.91	0.93	0.94	0.94	0.93	0.91	0.89	0.88	0.86	0.85	0.84
Mar	0.78	0.8	0.82	0.83	0.84	0.83	0.82	0.8	0.78	0.76	0.75	0.74
Apr	0.89	0.92	0.93	0.94	0.94	0.93	0.91	0.89	0.88	0.86	0.85	0.84
May	0.89	0.91	0.93	0.94	0.94	0.93	0.91	0.89	0.88	0.86	0.85	0.84
Jun	0.89	0.91	0.92	0.93	0.93	0.93	0.92	0.89	0.88	0.86	0.85	0.84
Jul	0.86	0.88	0.9	0.91	0.91	0.91	0.89	0.87	0.86	0.84	0.83	0.82
Aug	0.75	0.77	0.79	0.8	0.8	0.8	0.78	0.76	0.75	0.73	0.72	0.71
Sep	0.67	0.69	0.7	0.71	0.72	0.71	0.7	0.68	0.66	0.64	0.63	0.62
Oct	0.87	0.9	0.91	0.92	0.92	0.91	0.9	0.87	0.86	0.84	0.83	0.82
Nov	0.78	0.8	0.81	0.82	0.82	0.81	0.8	0.78	0.76	0.74	0.73	0.72
Dec	0.47	0.49	0.51	0.52	0.52	0.51	0.49	0.47	0.46	0.44	0.43	0.42
Year	0.79	0.81	0.83	0.84	0.84	0.83	0.82	0.8	0.78	0.76	0.75	0.74

TABLE IX: CASE STUDIES RESULTS

Case	Season and time	Load demand	SoC	P_{net}	DG value
Case 1	Summer [August] 9:00 p.m	2000 kWh	73%	−0.434	0
Case 2	Winter [December] 9:00 p.m	2000 kWh	23%	−0.434	63.5%

TABLE X: BENEFITS OF UTILIZING THE INTEGRATED SYSTEM OVER RUNNING SEPARATELY

Facility #	Load demand (MWh/day)	System power (kWp)	No. of PV module (Units)	PV module area (m2)	BESS capacity (Ah)	Unused energy (kWh/year)
Facility 1	14.5	3105	7056	15699	13872	318403
Facility 2	6.22	1433	3259	7245	5202	305014
Facility 3	0.78	180	408	908	1734	35670
Facility 4	2.2	493	1120	2492	1734	89945
Facility 5	0.6	135	306	681	1734	22492
Total	24.3	5346	12149	27025	24276	771524
Integrated approach	24.3	5242	11914	26508	24276	603452
Differences	0	104	235	517	0	168072

Note: Green color indicate positive impact.

carbon emissions achieved by transitioning from the conventional electrical system to the proposed photovoltaic system with the fuzzy energy management system is also computed and is compared with that obtained in the current scenario.

6.1. Case Studies

6.1.1. Case 1

At 9 pm on a summer day, the load demand for all the five facilities is 2000 kWh given by Tables I–V. The SoC of the batteries corresponding to each hour over the year is shown in Table VIII. From this Table, it can be observed that the SoC at 9 pm is 73%, P_{net} is −0.434 and thus the Power generated by the diesel generator is zero.

6.1.2. Case 2

The similar scenario on a winter day indicates that the SoC to be 23% and the power generation by the diesel generator generates 63.5% of the total power generation as given in Table IX.

The integration of a combined photovoltaic (PV) system, an energy management system, and a shared battery system for a sports complex, especially when the facilities are in close proximity, presents significant advantages. Utilizing a combined system for multiple sport facilities instead of individual PV systems enables efficient resource utilization and improved energy management. The shared battery system can accumulate surplus energy during periods of high PV generation from multiple facilities and subsequently distribute it during periods of heightened demand. This not only enhances energy efficiency but also reduces the necessity for separate energy storage systems for each facility.

In addition, by aggregating the thermal loads from all the facilities, it becomes feasible to employ a larger sand battery, which is a technology specifically engineered for thermal energy storage. By employing this integrated strategy, it is possible to achieve more efficient operations, enhanced energy conservation, and financial benefits, rendering it a competent option for a sports complex comprising several closely situated facilities, in addition

to the ability to use a shared back up system for all the facilities. These details are consolidated in Table X.

7. CONCLUSION

This research has proposed a fuzzy controlled PV Microgrid as a comprehensive solution for addressing the energy requirements of a university sports complex in Saudi Arabia. It achieves this by integrating renewable energy sources, advanced energy storage technologies, and innovative control systems. Through a detailed analysis of the sports complex's facilities and their respective energy needs, the study has identified opportunities for implementing renewable energy solutions, particularly solar photovoltaic systems. The proposed microgrid design, coupled with a fuzzy logic-based central monitoring and control system, offers an effective approach of energy consumption and effective utilization of various energy sources in the sports complex. The findings of this study can serve as a foundation for future sustainable energy initiatives within the university and contribute to the broader efforts of transitioning to a greener and more environmentally responsible future.

Furthermore, this research aligns with national objectives for renewable energy adoption and carbon emission reduction in Saudi Arabia. By harnessing the abundant solar resources available in the region and leveraging innovative energy storage technologies, it contributes to the Kingdom's transition towards a more sustainable and resilient energy infrastructure. The proposed solution also highlights the significant reduction in carbon emissions, emphasizing the environmental benefits of transitioning to renewable energy sources and advanced energy management systems. This reduction in carbon emissions not only supports national goals but also sets a precedent for similar initiatives in other sectors, showcasing the potential for widespread environmental impact.

CONFLICT OF INTEREST

The authors declare that they do not have any conflict of interest.

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