IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Design Of A Hybrid Off-Grid Energy System For Military Stations

[1]Ankit Mandaviya, [2]Manan Desai

[1]Reserch Scholar, [2]Assistant Professor

[1,2] Electrical Engineering Department,

[1,2] Dr. Subhash University, Junagadh, India

Abstract: Military stations, especially those deployed in remote or conflict-prone areas, face critical challenges in maintaining reliable, secure, and sustainable energy supplies. Traditionally, diesel generators have been the primary source of energy, but they impose high operational costs, fuel logistics issues, and carbon emissions. This paper presents the design and analysis of a hybrid off-grid energy system for military stations, integrating photovoltaic (PV) solar panels, wind turbines, battery energy storage systems (BESS), and a diesel generator as backup. This study evaluates the performance of the proposed system under varying climatic and operational conditions. Results indicate that the hybrid configuration can reduce diesel fuel consumption by up to 60%, enhance energy resilience, and provide secure, deployable, and sustainable power for military operations.

Index Terms – Hybrid Energy System, Military Stations, Off-Grid Power, Renewable Energy, Microgrid

1. Introduction

The global COVID-19 pandemic has highlighted the critical importance of mobile and reliable energy supply systems for temporary infrastructures such as mobile hospitals, testing laboratories, and first-aid stations. Beyond healthcare, the demand for quickly deployable energy solutions extends to outdoor events, refugee shelters, and—importantly—military operations. In the military domain, rapidly deployable energy supply systems are vital for maintaining mission readiness, powering essential services, and ensuring the comfort and safety of troops in remote and hostile environments.

Temporary military camps, similar to refugee settlements, face significant challenges in terms of energy efficiency, resilience, and sustainability. Current estimates indicate that approximately 500 temporary military camps are deployed worldwide, with about 20,000 NATO troops actively engaged in missions at any given time [1]. Energy consumption in these camps is considerably higher compared to conventional buildings, largely due to the poor thermal performance of lightweight tent structures and the reliance on diesel-powered HVAC systems [2,3]. Studies report that the U.S. military alone spends around $20.2 billion annually on air conditioning in Iraq and Afghanistan missions, reflecting the massive energy burden and fuel logistics associated with sustaining such operations [4].

At present, diesel generators remain the primary energy source for military camps due to their portability and rapid deployment. However, their reliance on continuous fuel supply chains poses significant vulnerabilities—both in terms of cost and security. In fact, the transportation and delivery of fuel to remote bases often exceed the cost of the fuel itself, while simultaneously exposing supply convoys to operational risks [6,9]. Furthermore, the environmental impact of fossil-fuel-based energy in temporary camps adds another layer of concern, prompting international initiatives, including NATO efforts, to improve energy efficiency and reduce fossil dependency in deployable military infrastructure [5].

The growing interest in renewable-based hybrid power systems offers promising alternatives. Photovoltaic (PV) systems, in particular, are safe, clean, and relatively easy to deploy, making them an attractive solution for off-grid military applications [10,11]. Several studies have demonstrated the feasibility of mobile PV-powered units for autonomous electricity generation in temporary structures [12,13]. However, renewable sources alone cannot ensure continuous supply due to their inherent intermittency, necessitating the integration of hybrid solutions that combine renewables with backup storage and limited generator use [6,8]. For military applications, such mobile hybrid energy units can provide electricity for critical services including communications, HVAC systems, refrigeration of medicines, lighting, and sterilization equipment—all essential for maintaining operational capability and troop welfare in forward-deployed environments [6,7]. By integrating renewable energy technologies into mobile platforms such as trailers, energy supply units can be quickly deployed, scaled, and relocated according to mission requirements.

This paper presents the concept of a mobile hybrid PV-based energy supply unit for military applications, emphasizing its role in reducing fossil fuel dependence, improving energy security, and supporting sustainable field operations. The proposed system is designed for rapid deployment, adaptability, and scalability to meet the evolving energy needs of military camps while contributing to broader objectives of energy efficiency and sustainability.

Camp Location (India)	**Population**	**Costs (for electricity generation with diesel fuel)**	**Energy-related costs in the global budget**	**Energy consumed per household**
Jammu (Jammu & Kashmir) – Refugee camps for displaced populations	~15,000	~45 k$/year	~10%	~11 $/month (≈6–8% of total household earnings)
Mizoram (Northeast India) – Refugee settlements (Bru/Reang community camps)	~35,000	~0.35 M$/year	~18%	~16 $/month (≈20–22% of total household earnings)

2. System Design and Architecture

The proposed hybrid system integrates the following components:

1. **Photovoltaic (PV) panels** – primary renewable source, mounted on modular structures for rapid deployment.
2. **Battery Energy Storage System (BESS)** – lithium-ion based storage for short-term load balancing and autonomy.
3. **Diesel generator** – backup system for critical load support during low renewable generation periods.
4. **Energy Management System (EMS)** – controls power flow, prioritizes renewable energy, and manages storage.

2.1 Load Profile of Military Stations

Military stations operate under extreme and diverse environmental conditions, which strongly influence their energy demand profiles. In India, the armed forces maintain permanent and temporary camps in high-altitude cold regions (e.g., Siachen Glacier, Leh-Ladakh), hot desert regions (e.g., Rajasthan), and tropical climates. Each scenario creates unique requirements for HVAC (heating, ventilation, air conditioning), lighting, communication, and critical systems.

1. High-Altitude, Low-Temperature Military Camps (e.g., Siachen, Ladakh at 3,000–6,000 m)

- Temperature range: –40 °C to –10 °C in winters.
- Primary loads:
  - Heating of shelters (electric heaters + diesel-based heating).
  - Medical equipment & warming of medicines.
  - High-energy demand for water heating and food preparation.

  - Communication and surveillance systems.
- Load profile characteristics:
  - Peaks during winter nights (heating load).
  - Continuous base load due to communication, medical, and security systems.
- Energy demand per soldier: Estimated 4–5 kWh/day, mostly HVAC-related [14–16].
- Current practice: Diesel gensets + kerosene/paraffin heaters; fuel transport is logistically costly [17].

2. Hot Desert Camps (e.g., Rajasthan, Thar Desert)

- Temperature range: 35–50 °C in summers.
- Primary loads:
  - Air conditioning and cooling dominate demand.
  - Refrigeration for medicines, food, and electronics.
  - Lighting and water pumping (borewells).
- Load profile characteristics:
  - Peak demand during daytime (AC load).
  - Night demand moderate (lighting + communications).
- Energy demand per soldier: Estimated 3–4 kWh/day, mostly cooling and refrigeration [18,19].
- Current practice: Diesel generators with evaporative coolers/air conditioners [19].

3. Moderate Climate Bases (Plains/Tropical Regions)

- Temperature range: 15–35 °C.
- Primary loads:
  - Balanced between cooling, lighting, and IT/communications.
  - Less heating/cooling demand compared to extremes.
- Load profile characteristics:
  - Two peaks: morning (lighting, cooking) & evening (lighting, communications).
- Energy demand per soldier: ~2–3 kWh/day [19,20].

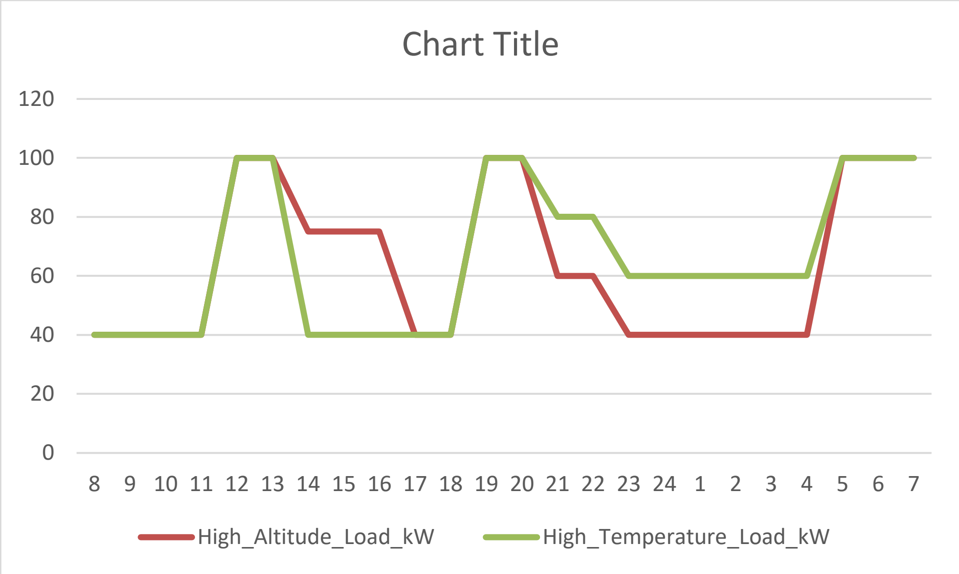

Figure 1. Load Profile

3. Methodology

In this study, a containerized hybrid energy system (CHES) for military camps was designed and analyzed using MATLAB/Simulink simulations. The design criteria included evaluating different technologies for energy generation and storage, considering their applicability in containerized solutions for rapid deployment during emergency scenarios. The selection of system components was based on sizing calculations, available container space, logistical constraints, maintenance requirements, and safety considerations. Each technology was modelled in detail to assess its technical and operational performance.

The simulation focused on a baseline military camp with 150 personnel. The energy demand, comprising electrical and thermal loads, was derived from historical deployment data, including electricity generation and diesel-heating requirements. Hourly load profiles were constructed in MATLAB to capture the variability in energy consumption due to occupancy, climate conditions, and operational schedules. Climate data for the targeted region (representative of high-latitude temperate zones) were incorporated to accurately simulate seasonal variations in energy demand and renewable energy availability [12,16].

The hybrid system included photovoltaic (PV) modules, diesel generators, and battery energy storage systems (BESS). Dynamic energy balance simulations were performed in MATLAB to determine the optimal operation of the generators and battery storage, including charging and discharging strategies, at each time step. The simulation framework allowed for analysis of multiple system configurations, enabling comparisons of energy supply strategies, load management, and integration of energy efficiency measures such as advanced insulation or demand-side management [15].

For economic evaluation, capital costs, replacement costs, operation and maintenance expenses, fuel costs, and interest rates were incorporated into the MATLAB model to calculate the net present cost (NPC) for each configuration. Optimization routines were implemented to identify the configuration that minimizes NPC while ensuring reliable supply of both electrical and thermal energy [15]. Sensitivity analyses were also performed to evaluate system performance under variations in fuel costs, battery lifetimes, and renewable energy generation levels.

The MATLAB-based dynamic simulations provided a flexible and accurate platform for assessing both technical feasibility and economic viability of hybrid energy solutions for military camps. This approach enabled the identification of an optimal system configuration capable of reducing fuel consumption, minimizing operational costs, and maintaining energy security under diverse climatic conditions.

3.1 Case Study

Remote Temporary Camps (RTCs) are established to provide a comprehensive range of facilities, including accommodations, administrative shelters, ablutions, maintenance and storage areas, hangars, and kitchens [21]. The standard accommodation within these camps consists of military-style tents, which are deployed globally and designed to house between four and ten individuals. These living quarters are typically situated in a condensed area adjacent to shared ablution facilities [22]. The population supported by an RTC can fluctuate significantly daily, influenced by operational tempo and periodic personnel rotations [23]. To support hygiene, ablution units—each comprising a shower, a toilet, and a sink—are provided at a ratio of one unit for every ten camp members [21].

The utility infrastructure in RTCs is characterized by multiple, independent systems for electrical power, heating and cooling, fuel and water management, and waste disposal [24]. A significant challenge is that these systems are not designed to optimize energy efficiency. The predominant energy management strategy relies on diesel-powered generators for all electricity production [22]. Electrical power is supplied to the camp from several generator farms, which typically incorporate 300 kW, 350 kW, and 500 kW single-speed generator models [25]. To mitigate the inefficiencies of low-load operation, generators are kept running at optimal levels through the use of load banks. This practice results in any excess electricity being diverted to the load banks, where it is converted into waste heat [26]. For climate control, heating is provided by diesel-fired space heaters, while cooling is managed by electric environmental conditioning units. These individual HVAC units are attached to each tent and controlled directly by the occupants [27].

3.2 Hybrid Energy System (HES) Design

The Smart Hybrid Energy System (SHES) is engineered for versatile operation, capable of functioning in a stand-alone mode or connected to a local grid [1]. This system integrates several key technologies into a single, managed platform: a photovoltaic (PV) array, an energy storage system, existing diesel generators, a waste-heat-to-energy recovery unit (WHRU), a solar hot water (SHW) system, and a central Energy Management System (EMS) [2].

System Components and Configuration

- **Photovoltaic Array**: The primary renewable power source is PV array [2]. It is composed of high-efficiency (21%) modules anchored with a south-facing, optimized tilt angle [3]. This system is sized to cover peak electrical loads, with the exception of cooling demands. The limit was a deliberate choice considering military requirements for transportability, rapid reinstallation, spatial limitations, and high initial costs that made a larger system impractical [4, 5].
- **Energy Storage**: To counter the intermittent nature of solar power, the SHES incorporates a containerized sodium-sulfur (NAS) battery system [6]. This unit was selected for its cost-effectiveness and technical specifications, including a large capacity (1250 kWh), a maximum discharge output of 286.1 kW, a long duration (4.4 hours), and a 20-year lifespan [7]. A Battery Management System (BMS) protects and monitors the cells, operating with a minimum state of charge of 40% and a cost-optimized setpoint of 80% [8].
- **Backup and DG Systems**: Existing internal combustion diesel generators are integrated into the microgrid to guarantee a continuous power supply, with a minimum part-load ratio of 15% assumed for their operation [9, 25]. The system also includes two thermal technologies:
- **Energy Management System (EMS)**: The EMS is the core of the microgrid, controlling all components to ensure grid stability [14]. It actively balances energy generation and consumption, prioritizing the use of renewable sources to optimize system performance. The EMS also provides real-time remote monitoring, allowing for centralized and informed operational control [15, 26].

The design emphasizes redundancy to ensure continuous operation even if a subsystem fails. By prioritizing renewable energy and battery power, the hybrid configuration reduces generator runtime, leading to lower fuel consumption and less frequent maintenance [17]. The EMS contributes to overall system reliability by identifying potential maintenance issues before they escalate, improving response times and streamlining maintenance schedules [18].

For ease of deployment, the system is designed to be a "plug-and-play" solution. It is prewired, preconfigured, and utilizes existing state-of-the-art components, ensuring replacement parts are widely available in the market. This approach allows for rapid installation with only minor on-site assembly required [19, 23].

Conclusion

This paper presents a novel energy solution for military base camps, which significantly improves upon existing systems. By integrating a microgrid with renewable resources, energy storage, and waste heat recovery, the approach drastically reduces the need for fuel supply to remote tactical camps. The proposed energy solution for military base camps offers significant improvements over existing systems. The full implementation of these technologies in a temperate climate can reduce fuel consumption and annual CO2 emissions by up to 37%. Even in extreme climates, optimizing solar collector tilt can achieve reductions ranging from 21% to 39%. The system's smart microgrid, combined with energy storage, enhances grid reliability by providing superior voltage and frequency stability, thereby extending the lifespan of equipment. Finally, a centralized Energy Management System (EMS) allows for informed decision-making through real-time monitoring and control. This system also features configurable automatic load distribution, which can further reduce energy consumption during both routine operations and unplanned events.

References

[1] NATO. (2020). *NATO Secretary General's Annual Report 2019*. NATO Public Diplomacy Division.

[2] Dodoo, A., Gustavsson, L., & Sathre, R. (2014). Building energy-efficiency standards in a life cycle primary energy perspective. *Energy and Buildings*, 77, 415–426.

[3] Bristow, D. N., Kennedy, C. A., & Moore, E. A. (2012). Urban metabolism and greenhouse gas emissions from military installations. *Journal of Industrial Ecology*, 16(3), 407–418.

[4] Amos, H. (2011). U.S. Military's $20 Billion Air Conditioning Bill. *Bloomberg*.

[5] NATO Energy Security Centre of Excellence. (2019). *Energy Efficiency in Deployable Military Camps*. Vilnius, Lithuania.

[6] Grafham, O. (2016). *Energy for Displaced People: Challenges and Solutions*. Chatham House Report.

[7] UNHCR. (2015). *Global Strategy for Safe Access to Fuel and Energy (SAFE)*. United Nations High Commissioner for Refugees.

[8] Lahn, G., & Grafham, O. (2015). *Heat, Light and Power for Refugees: Saving Lives, Reducing Costs*. Chatham House.

[9] Foster, V., & Briceño-Garmendia, C. (2010). *Africa's Infrastructure: A Time for Transformation*. World Bank.

[10] Green, M. A., et al. (2017). Solar cell efficiency tables (version 50). *Progress in Photovoltaics: Research and Applications*, 25(7), 668–676.

[11] REN21. (2020). *Renewables 2020 Global Status Report*. REN21 Secretariat, Paris.

[12] Mancarella, P. (2014). MES (multi-energy systems): An overview of concepts and evaluation models. *Energy*, 65, 1–17.

[13] Al Busaidi, A. S., Kazem, H. A., Al-Badi, A. H., & Khan, M. F. (2016). A review of optimum sizing of hybrid PV–wind renewable energy systems in Oman. *Renewable and Sustainable Energy Reviews*, 53, 185–193.

[14] Indian Army. (2017). *Siachen Glacier: The Coldest and Highest Battlefield*. Ministry of Defence, Government of India.

[15] Kumar, S., & Singh, V. (2018). Energy requirements and logistics of sustaining high altitude military bases. *Defence Science Journal*, 68(4), 342–349.

[16] Directorate of Military Operations. (2019). *Siachen Logistics and Energy Challenges*. Integrated HQ of MoD (Army), New Delhi.

[17] NATO Energy Security Centre of Excellence. (2019). *Energy Efficiency in Deployable Military Camps*. Vilnius, Lithuania.

[18] TERI. (2020). *Energy Use in Defence Installations in India: Opportunities for Efficiency and Renewables*. The Energy and Resources Institute, New Delhi.

[19] Gupta, R., & Bansal, N. K. (2019). Assessment of power demand in Indian defence establishments in desert conditions. *Journal of Renewable and Sustainable Energy*, 11(6), 065902.

[20] International Energy Agency (IEA). (2021). *Energy Access and Security in Remote Areas*. Paris: IEA.

21] Department of the Army. (2018). *ATP 3-37.10 Base Camp Design, Construction, and Operations*. Headquarters, Department of the Army.

[22] Eisman, D., & Usher, L. (2021). *Reducing Fuel Demand in the U.S. Department of Defense: A Review of Current Initiatives*. RAND Corporation.

[23] Pincus, L., et al. (2019). *Sustainment of Army Forces in Operation Iraqi Freedom: Major Findings and Recommendations*. RAND Corporation.

[24] U.S. Army Corps of Engineers. (2020). *Energy and Water Management for Contingency Bases*. Engineer Research and Development Center (ERDC/CERL TR-20-13).

[25] DiMascio, A. J., & Geyer, S. M. (2017). *Microgrid and Renewable Energy Integration for Military Installations*. MIT Lincoln Laboratory Technical Report.

[26] Johnson, M. R., & Lamm, L. (2019). *Operational Energy Series: Improving Efficiency of Tactical Power Generation*. Naval Postgraduate School.

[27] Walsh, T., & Burdic, C. (2022). *Occupant Behavior and Energy Consumption in Temporary Military Shelters*. Journal of Military and Strategic Studies, 23(1), 45-62.