MAES AS A DATA-DRIVEN TRAINING PLATFORM: DAYLIGHT HIGH-LOAD OPERATION WITH PHOTOVOLTAIC SUPPORT

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Abstract: *This paper presents a short experimental episode based on the MAES prototype - Mobile Module for Ensuring Energy Autonomy from Sustainable Sources, interpreted as a data-driven training platform for tactical energy autonomy [1]. The analysis goes one step further than previously published research by focusing on daylight operation under high three-phase load and significant photovoltaic contribution. During the analyzed interval, MAES supplied an AC load of approximately 11-12 kW, while the photovoltaic subsystem generated between 4.0 and 5.1 kW instantaneously. The measured data show that solar input reduced the battery discharge power from values close to 12 kW, typical for operation without photovoltaic production, to approximately 7.2-7.9 kW. The paper also integrates short-term energy balance screenshots, which indicate that cloudy days affected solar yield and reduced the expected photovoltaic contribution. The results confirm the usefulness of MAES as a living laboratory for military technical education and as a basis for further development of predictive autonomy models integrating load, PV production, battery state of charge and operational constraints.*

Keywords: *MAES, data-driven training platform, photovoltaic support, LiFePO4 storage, tactical energy autonomy, VRM monitoring, energy management, military education*

1. INTRODUCTION

Deployable military infrastructures increasingly depend on reliable, monitored and adaptable energy systems. Command posts, communication nodes, field sensors and radar-related applications require stable power supply, while the logistical cost and acoustic signature of diesel generators remain important operational limitations. In this context, hybrid systems combining photovoltaic generation, electrochemical storage, inverter-based conversion and remote monitoring can support both operational resilience and applied technical education.

From the perspective of operational energy, deployable infrastructures should be considered not only as consumers of electricity, but as mission systems whose effectiveness depends on resilient power supply, fuel economy and real-time energy awareness. NATO identifies energy security as a relevant dimension of Allied resilience, because disruptions in energy supply can affect both national security and military operations [2]. Consequently, command posts, communication nodes and radar-related systems require energy solutions that reduce dependence on continuous generator operation while preserving operational continuity.

Military microgrids respond to this requirement by combining conventional generators, photovoltaic sources, energy storage, efficient loads and intelligent power management. NATO Energy Security Centre of Excellence materials indicate that microgrids integrating diesel generators, renewable sources, efficient consumers and intelligent management have demonstrated fuel-saving potential for deployed camps [3].

NATO smart-energy initiatives also show that photovoltaic systems, solar trailers and hybrid microgrid demonstrators can be used in deployed military environments, provided that their limitations regarding irradiance, available surface, orientation and maintenance are properly understood [4].

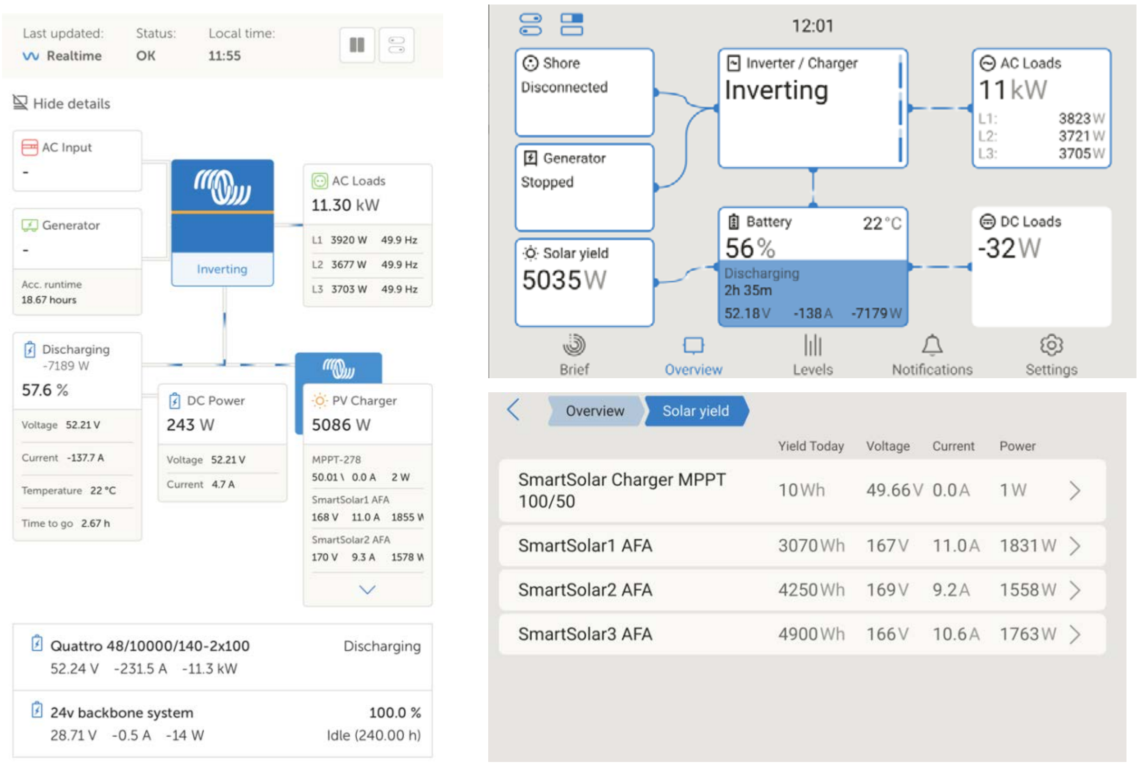
Recent microgrid research confirms the importance of distributed generation, storage, control strategies and information technologies for resilient energy systems [5]. In the military field, tactical microgrids are discussed as a means to reduce fuel demand, improve electrical resilience and lower acoustic or thermal signatures [6], while broader defence-energy approaches emphasize the need for architectures able to combine resilience, autonomy and operational planning [7]. In this context, MAES can be interpreted as a small-scale deployable military microgrid and as a data-driven platform for future predictive energy management.

The MAES prototype was previously introduced as a mobile energy autonomy solution based on renewable generation and battery storage. The present paper does not repeat the complete architectural description of the prototype. Instead, it provides a concise experimental episode based on real monitoring data, focusing on daylight operation under high load and partial photovoltaic support.

The main objective is educational. MAES is considered not only as an energy platform, but also as a living laboratory. Students can observe the relationship between AC load, photovoltaic production, battery discharge, state of charge and estimated autonomy. Such a training context is particularly relevant for modern military technical education, which increasingly requires the use of digital platforms, real data and applied experimentation [8, 9].

2. EXPERIMENTAL CONTEXT AND MONITORED VARIABLES

The analyzed episode corresponds to daylight operation with a high three-phase load.



Last updated: Realtime
Status: OK
Local time: 11:55

AC Input -
Generator -
Acc. runtime 18.67 hours

AC Loads 11.30 kW
L1 3920 W 49.9 Hz
L2 3677 W 49.9 Hz
L3 3703 W 49.9 Hz

Discharging -7189 W
57.6 %
Voltage 52.21 V
Current -137.7 A
Temperature 22 °C
Time to go 2.67 h

DC Power 243 W
Voltage 52.21 V
Current 4.7 A

PV Charger 5086 W
MPPT-278
50.01 \ 0.0 A 2 W
SmartSolar1 AFA
168 V 11.0 A 1855 W
SmartSolar2 AFA
170 V 9.3 A 1578 W

Quattro 48/10000/140-2x100 Discharging
52.24 V -231.5 A -11.3 kW

24v backbone system 100.0 %
28.71 V -0.5 A -14 W Idle (240.00 h)

12:01

Shore Disconnected
Generator Stopped
Solar yield 5035 W
Inverter / Charger Inverting
AC Loads 11 kW
L1: 3823 W
L2: 3721 W
L3: 3705 W
Battery 22 °C
56 %
Discharging
2h 35m
52.18 V -138 A -7179 W
DC Loads -32 W

	Yield Today	Voltage	Current	Power
SmartSolar Charger MPPT 100/50	10 Wh	49.66 V	0.0 A	1 W
SmartSolar1 AFA	3070 Wh	167 V	11.0 A	1831 W
SmartSolar2 AFA	4250 Wh	169 V	9.2 A	1558 W
SmartSolar3 AFA	4900 Wh	166 V	10.6 A	1763 W

FIG. 1 (a) Daylight MAES dashboard under high AC load and PV contribution (b) Overview display showing PV support and battery discharge; **(**c) MPPT-level solar production values during the daylight test

The system operated in inverter mode, with the AC input disconnected and the generator stopped. Consequently, the load was supplied by the combined contribution of photovoltaic generation and the LiFePO4 battery bank. The available screenshots include the main Cerbo GX/VRM dashboard, overview pages, MPPT-level solar yield pages and short-term energy balance charts.

The relevant monitored variables are AC load, instantaneous PV power, battery state of charge, battery discharge power and, where available, MPPT voltage and current. These variables are sufficient for a preliminary operational interpretation because they allow the net battery burden to be assessed during high-load operation. From a didactic point of view, they also allow students to calculate the share of solar contribution and to compare ideal autonomy calculations with real operating conditions.

Figures 1.a-c present three distinct screenshots used as experimental evidence. They were kept as separate figures in order to allow flexible arrangement in the final version of the paper and to preserve the visibility of solar production values, especially the PV Charger, Solar Yield and MPPT-level power indicators.

3. INSTANTANEOUS PHOTOVOLTAIC SUPPORT UNDER HIGH LOAD

The values in Table 1 show that the photovoltaic subsystem supplied between approximately 37% and 46% of the instantaneous AC load. The clearest operating point is at 11:55, when the AC load was 11.30 kW, PV production was 5.086 kW and the battery discharge power was approximately 7.189 kW. Therefore, almost 45% of the instantaneous demand was covered by solar generation.

Table 1. Instantaneous values extracted from MAES daylight monitoring

Time	**AC Load (kW)**	**PV Power (kW)**	**Battery SOC (%)**	**Battery Power (kW)**	**PV Share (%)**	**Observation**
11:37	~11.0	4.055	63	-7.943	36.9	high load, partial PV support
11:39	~12.0	4.834	63	-	40.3	PV production close to 5 kW
11:55	11.30	5.086	57.6	-7.189	45.0	clear reduction of battery burden
12:01	~11.0	5.035	56	-7.179	45.8	stable PV + battery operation

This result is relevant because, in operation without solar production, a similar load requires the battery bank to supply almost the entire power demand. In the daylight case, the PV subsystem reduces the net battery burden by roughly 4-5 kW. This translates into longer autonomy, lower discharge stress and reduced need for generator intervention under favorable solar conditions.

The graphical representation in FIG. 2 compares the AC load, measured PV production, battery discharge and battery state of charge. The upper textual title was deliberately removed from the graph; the explanatory title is kept only in the caption below the figure, in accordance with the Review of the Air Force Academy template requirements for figure captions.

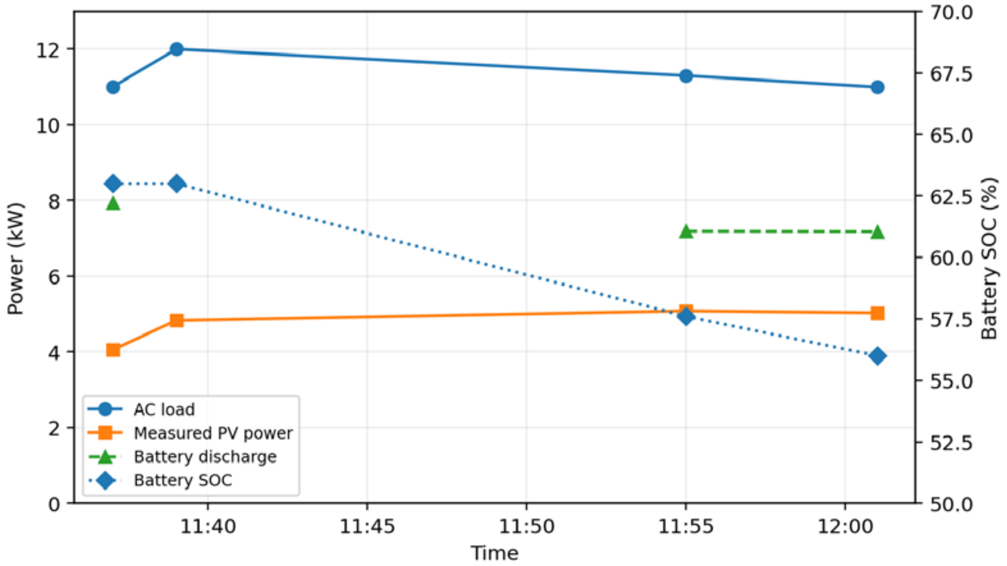


FIG. 2. AC load, measured PV production, battery discharge and SOC during daylight high-load operation

4. SHORT-TERM ENERGY BALANCE AND CLOUDY-DAY INFLUENCE

Instantaneous measurements are useful for explaining the energy flows at a given moment, but the operational relevance of MAES also depends on energy balance over longer intervals. The VRM monitoring screenshots provide several interval-based views in which consumption, solar yield and battery state of charge are displayed simultaneously. These views are particularly useful for teaching because they show how daily energy availability depends on both load profile and weather conditions.

Table 2. Short-term energy balance from VRM screenshots

Monitoring interval	Consumption (kWh)	Solar yield (kWh)	Interpretation
27-28 May	65.4	42.4	high consumption; PV covered a significant part
28-30 May	31.6	32.5	solar yield comparable to consumption
30 May-1 Jun	1.4	21.7	low load; favorable battery recovery
1-2 Jun	1.9	4.1	cloud-affected day with modest surplus

The analyzed interval contained several cloudy periods. Consequently, solar production was lower than what would normally be expected under fully clear-sky conditions for the installed photovoltaic capacity. This explains why, in some intervals, solar yield remained below consumption even though the platform was operating during daylight hours. Conversely, when the load was reduced, even limited solar production was sufficient to increase or maintain the battery state of charge.

2026-05-27 04:10 to 2026-05-28 19:

To AC Input 0 kWh
From AC Input 0 kWh
Generator 0 kWh
Consumption 65.4 kWh
Solar 42.4 kWh

2026-05-28 19:24 to 2026-05-30 10:

To AC Input 0 kWh
From AC Input 0 kWh
Generator 0 kWh
Consumption 31.6 kWh
Solar 32.5 kWh

2026-05-30 10:38 to 2026-06-01 01:

To AC Input 0 kWh
From AC Input 0 kWh
Generator 0 kWh
Consumption 1.4 kWh
Solar 21.7 kWh

2026-06-01 01:52 to 2026-06-02 17:

To AC Input 0 kWh
From AC Input 0 kWh
Generator 0 kWh
Consumption 1.9 kWh
Solar 4.1 kWh

FIG. 3 a-d. Energy balance for 27 May -1 June interval

4. EDUCATIONAL AND OPERATIONAL INTERPRETATION

The main educational value of this episode is that students can work with real data instead of idealized values. For the 11:55 operating point, they can calculate the PV contribution as 5.086 kW divided by 11.30 kW, resulting in approximately 45%. They can also observe that the remaining power demand is covered by the battery bank and that the overall system remains in inverter mode, with the generator stopped and the AC input disconnected.

This type of analysis supports applied training in renewable energy, power electronics, battery management, energy logistics and operational planning. It can also be connected to data-driven decision support. The interpretation of measured data, alarms, state of charge and load profiles is consistent with broader approaches in which operational information is transformed into decision support indicators [12].

From an operational perspective, the daylight scenario confirms that the hybrid PV-battery architecture is more flexible than a storage-only or generator-only solution. Under solar input, the battery discharge rate is reduced, autonomy is extended and the generator start can be delayed. This is relevant for mobile command posts, communication nodes and radar-related applications, where continuity of supply and reduction of acoustic signature are important operational requirements [13].

5. CONCLUSIONS

This paper presented a concise daylight operating episode of the MAES prototype under high load and significant photovoltaic contribution. The measured data show that, for an AC load of approximately 11-12 kW, instantaneous PV production of 4-5 kW can cover up to about 45% of the power demand and can reduce the battery discharge power to approximately 7.2-7.9 kW.

The interval-based screenshots further show that MAES operation must be interpreted not only through instantaneous power values, but also through short-term energy balance. During cloudy days, solar yield was affected and could not always cover consumption, even though it still reduced the energy deficit. When consumption was low, even modest solar production contributed to battery recovery.

The results confirm the role of MAES as a data-driven training platform and as a practical basis for future predictive autonomy models. Such models should integrate solar forecast, measured PV production, load profiles, battery state of charge, temperature effects and BMS constraints in order to support tactical energy planning for deployable military infrastructures.

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