MAES: A DEPLOYABLE ENERGY LABORATORY FOR AIR FORCE EDUCATION, RESEARCH AND TACTICAL POWER RESILIENCE

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Abstract: *MAES is a deployable energy laboratory developed within the "Henri Coandă" Air Force Academy to support specialized education, applied research and tactical energy resilience. The prototype integrates photovoltaic generation, $LiFePO_4$ battery storage, three-phase off-grid conversion, automatic source transfer and remote monitoring into a mobile platform designed for rapid field deployment. Its technical configuration includes 5.85 kWp of installed photovoltaic power, 40.96 kWh of energy storage capacity and 30 kVA of available three-phase power, allowing it to supply command posts, communication systems, educational equipment and radar-related applications. By using solar energy and electrochemical storage, the platform can reduce dependence on continuous diesel generator operation, while decreasing fuel consumption, acoustic signature and logistical vulnerability during field missions. From an educational and research perspective, MAES provides students and cadets with a practical environment for analyzing photovoltaic systems, MPPT algorithms, battery management, power conversion, automatic source transfer and remote energy monitoring. The paper highlights the role of MAES as a dual-use platform, capable of supporting both the training of future officers and the development of mobile energy autonomy solutions for realistic operational scenarios. The advantages of its modular architecture, the possibility of expansion by connecting multiple modules and the relevance of the concept for critical military infrastructures requiring high mobility, safety and operational continuity are also discussed.*

Keywords: *MAES, deployable energy laboratory, renewable energy, $LiFePO_4$ storage, photovoltaic systems, tactical energy resilience, off-grid systems, military education*

1. INTRODUCTION

This article presents the prototype of MAES - Mobile Module for Ensuring Energy Autonomy from Sustainable Sources - as an educational, applied research and tactical energy support platform. The paper continues the conceptual vision initially expressed in the article dedicated to MAES published in the Journal of the Air Force Academy, in which the need for a mobile platform capable of combining renewable generation, energy storage and operational use in the military environment was argued [1].

In its current form, the prototype goes beyond the level of a conceptual proposal and becomes a functional, testable, monitorable and usable system in the training process.

The priority of the article is the educational character of the MAES. The platform is analyzed first as a teaching and research laboratory, then as a system capable of powering a mobile command post and, thirdly, as a means of energy support for communication systems and applications associated with radiolocation.

This order reflects the institutional role of the "Henri Coanda" Air Force Academy, where the development of technical skills of students and cadets must be correlated with the real needs of the operational environment.

2. SCIENTIFIC AND INSTITUTIONAL CONTEXT

The digitization of higher military education and the integration of technical applicative platforms are important directions for the modernization of the educational process. Miron and Gherman highlight that the pandemic has accelerated the need for digitalization in academia, but also the need for educational tools capable of connecting teaching, experimentation and the use of modern technologies [2]. In a complementary direction, projects dedicated to surveillance and aviation security systems have shown the importance of coherent skills training in areas such as air surveillance, security, information management and interoperability [3].

MAES is part of this context by transforming energy into an object of applied study. Students don't just analyze formulas, schematics, or simulations, but can observe the actual operation of a three-phase off-grid system, track load and discharge curves, interpret data from MPPT controllers, analyze the role of the BMS, and evaluate system behavior in variable load scenarios. In this sense, the platform contributes to the shift from descriptive teaching to experiment-based and real-data training.

The importance of digitalization in higher military education is also supported by Meclea, Baldea and Boscoianu, who deal with the effects of post-Covid digitalization on educational processes and academic management [4]. For MAES, this perspective is relevant because the system is not only an energy ensemble, but also a digital node for monitoring, data generation and technical interpretation. Moreover, the use of data to support the decision is in line with the approaches to intelligent information management systems, in which operational data is transformed into decision support, as discussed by Pohrib, Goga and Pîslă in the analysis of intelligent ERP systems [5].

From a technical point of view, the integration of photovoltaic sources with electrochemical storage and MPPT algorithms is a consolidated direction in current research. Deliu, Cazacu, Deliu, Popa, Popa and Preda analyze the dynamic modeling and stability of PV-battery converters with global maximum power point tracking algorithms, aspects that are relevant for understanding the operation of MAES in variable solar production regime [6]. At the same time, Cristea, Popa, Manea and Popa deal with the automation of an autonomous platform powered by solar sources, which confirms the application interest in renewable sources in mobile and autonomous systems [7].

3. GENERAL ARCHITECTURE OF THE MAES SYSTEM

The MAES prototype is made as a mobile energy platform, installed on a chassis designed and built from scratch as off-road support and designed for rapid deployment in rough terrain. The system integrates photovoltaic generation, $LiFePO_4$ storage, three-phase conversion, automatic transfer between sources and local or remote monitoring.

The technical configuration includes 13 photovoltaic panels (1 for 24V automatic backbone and 12 distributed 4 each on each of the 3 distinct orientations/MPPT, one fixed horizontal and 2 lateral retractable up to 140°) of 450 Wp, resulting in an installed power of 5.85 kWp, a $LiFePO_4$ battery bank with a nominal capacity of 40.96 kWh and three inverters configured for three-phase power supply at 400 V. The technical values used in the article are based on the documentation internal design data sheet and on the data sheets of the main components [8-11].

The energy architecture is built on a 48 V and 51.2 V nominal DC bus, respectively, to which the storage subsystems, MPPT controllers and inverters are connected. The energy produced by photovoltaic panels is used primarily to power consumers and charge batteries. In the absence of solar production, the loads are powered by batteries, and in situations of necessity the system can use the external grid or diesel generator through the automatic transfer logic.

FIG. 1 MAES deployable platform with photovoltaic panels in operational position

Figure 1 shows the MAES system with the photovoltaic panels deployed. This image will support the description of the displacement of the platform and will highlight the difference between the footprint of the trailer and the capture area obtained after opening the side panels.

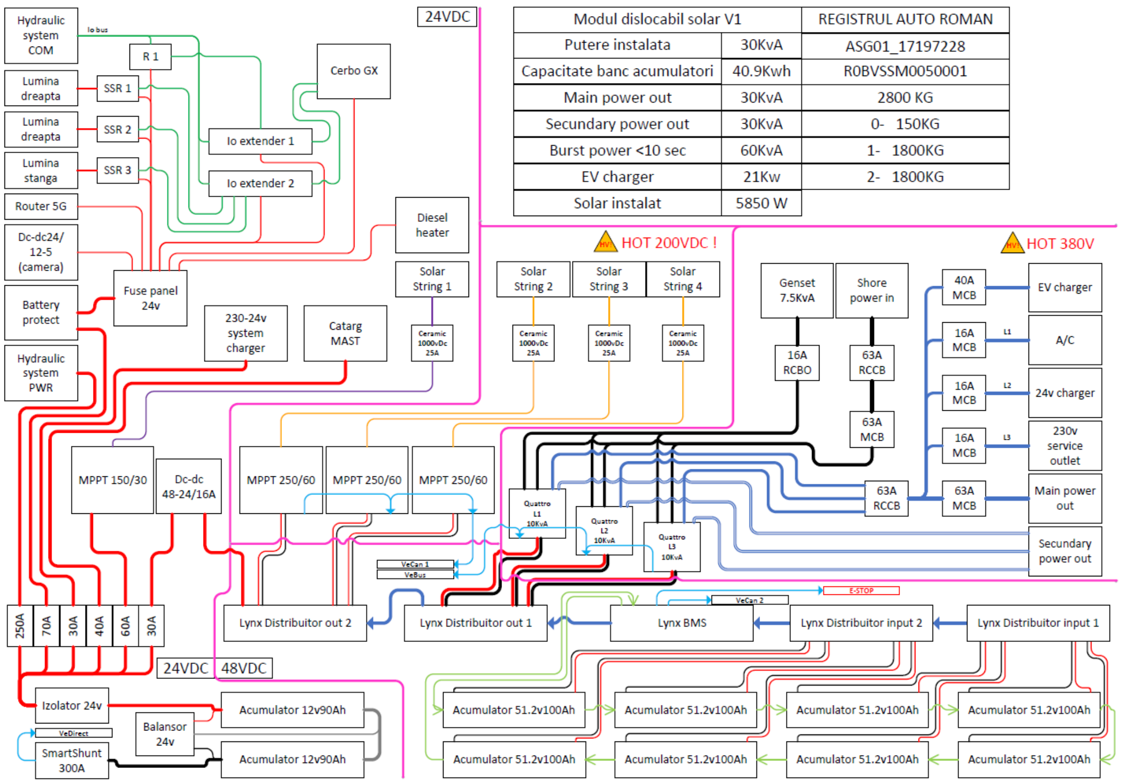

FIG. 2. General architecture of the MAES hybrid off-grid energy system

Figure 2 reveals the architecture of the system, from the PV panels and MPPT controllers to the battery bank, inverters, AC outputs, external source and backup generator. This scheme is necessary because it allows the tracking of energy flows and the role of each subsystem in autonomous functioning.

Table 1. Main technical parameters of the MAES prototype

Parameter	Value
Installed photovoltaic power	5.85 kWp
PV modules	13 × 450 Wp
Battery technology	$LiFePO_4$
Nominal storage capacity	40.96 kWh
DC bus	48 V / 51.2 V nominal
AC output	400 V three-phase
Continuous AC power	30 kVA
Peak AC power	60 kVA
Backup generator	7.5 kW diesel
Remote monitoring	Cerbo GX / VRM

The technical parameters in Table 1 indicate that the MAES is not just a low-power demonstration platform, but a system capable of feeding real loads, with a relevant operational and didactic profile. From this perspective, the platform is suitable for applied training, for testing energy autonomy scenarios and for evaluating the behavior of three-phase loads in off-grid mode.

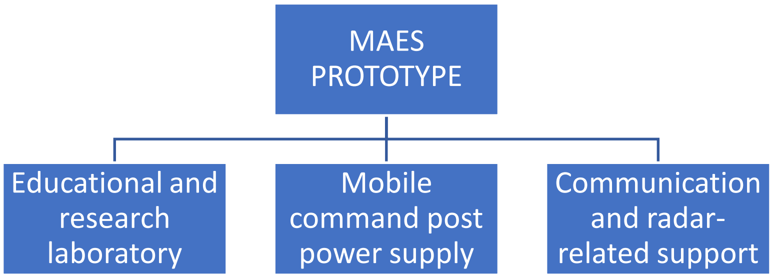

FIG. 3 The three primary directions of use of the MAES prototype

Figure 3 highlights the three directions of use: teaching and research laboratory, powering a mobile command post and energy support for communications and applications associated with radiolocation. The order of representation puts the educational role first, in accordance with the main objective of the project carried out through the R&D Sectorial Plan of the Ministry of National Defence.

Table 2. Main application directions of the MAES prototype

Application direction	Field	Energy relevance	Expected benefit
Educational and research laboratory	PV generation MPPT control LiFePO4 storage BMS monitoring Three-phase inverter VRM supervision	Real-time study of PV generation, storage, conversion and monitoring	Practical training and applied research
Mobile command post supply	Computers Lighting Climate control Auxiliary services Tactical autonomy Reduced fuel use	Variable loads from IT, communications, lighting and auxiliary systems	Reduced diesel generator runtime
Communication and radar-related support	Radio equipment Communication nodes Radar-related loads Field sensors Continuity of supply Tactical resilience	Stable three-phase power and source redundancy	Improved tactical power resilience

4. USE AS A TEACHING AND RESEARCH LABORATORY

The first direction of use of the MAES is educational. The platform allows students and cadets to directly observe the processes of energy production, conversion, storage and distribution. Instead of a limited approach to isolated components, MAES offers an integrated system, in which the operation of photovoltaic panels, MPPT controllers, batteries, BMS, inverters and automatic transfer between sources can be analyzed simultaneously.

From a didactic point of view, MAES can be used in laboratory activities for disciplines such as renewable energy sources, power electronics, power systems, automation, monitoring systems, data communications and energy logistics. Students can track photovoltaic production curves, calculate yields, analyze phase load balancing, interpret BMS alarms, and compare operating scenarios with or without solar input.

The research component is supported by the possibility of collecting operating data in real time. The data provided by the Cerbo GX and the VRM platform can be used for statistical analysis, range modelling, battery behaviour assessment and comparison of energy management strategies. In this way, the MAES can become an experimental infrastructure for bachelor's theses, dissertations, research projects and demonstration activities.

This perspective is compatible with research on the inspection, monitoring and maintenance of photovoltaic systems, where Cioacă, Popescu, Prisacariu, Pop and Vidan highlighted the potential of overhead solutions for the efficient monitoring of photovoltaic installations [12]. For MAES, this direction can be extended by integrating energy monitoring data, thermal images and preventive verification procedures for panels, connections and conversion equipment.

The relevance of this approach is further supported by the evolution of modern military communication systems, including troposcatter solutions for beyond-line-of-sight connectivity, as analyzed by Sârbu, Alexandrescu, and Galben in the context of resilient military networks and operational environments with limited infrastructure [13].

From the perspective of the human factor, the use of MAES as a didactic laboratory also allows the observation of the relationship between operator, interface and system. Rusu and Calefariu discuss the concept of Human Performance Envelope in aerospace activity, emphasizing the role of factors influencing operator performance in complex technological environments [14]. Therefore, MAES can be used not only for the study of energy, but also for training operators in data interpretation, decision-making and reaction to alarms or load variations.

Also, FIG. 2 represents a learning tool/platform, highlighting the main teaching modules: photovoltaic generation, MPPT control, battery management, three-phase conversion, ATS, remote monitoring and data analysis.

5. POWERING A MOBILE CONTROL STATION

The second direction analyzed is the supply of a mobile command post. Such a position may include computers, communications equipment, display systems, lighting, air conditioning, local servers, auxiliary equipment, and means of charging for portable devices. Under these conditions, the consumption profile is variable, but can reach values in the order of several kilowatts, depending on the technical configuration and the duration of the mission. MAES can help increase the autonomy of a mobile control station by reducing the uptime of the diesel generator. During the day, photovoltaic energy can partially or fully cover consumption and charge batteries.

In intervals without solar production, the battery bank can power critical loads, and the generator can only be used when the state of charge drops below a predetermined threshold. This hybrid logic reduces fuel consumption and increases logistics flexibility.

In the context of project management and adaptive systems, Sârbu and Țicușan discuss the concept of antifragility as a mechanism by which systems can become more robust under conditions of uncertainty [15]. Applied to MAES, this concept supports the idea that a modular energy infrastructure, monitored and capable of switching between different sources, is more adaptable than a solution based on a single energy source.

6. ENERGY SUPPORT FOR COMMUNICATIONS AND RADIOLOCATION-RELATED APPLICATIONS

The third direction of use is energy support for communication systems and radiolocation-related applications. In this case, continuity of supply, energy quality and the ability to sustain consumption peaks become essential requirements. Communications systems, network equipment, tactical servers, radio stations, and sensor support equipment require stable and predictable power, especially in deployed configurations.

With the three-phase output of 400 V and the available power of 30 kVA, the MAES can support significant loads, including equipment with transient starting modes. In the case of radiolocation-related applications, the platform should not be interpreted as a universal replacement for dedicated energy infrastructures, but as a support solution, extension of autonomy, temporary power supply or reduction of dependence on generator in well-defined scenarios.

An important advantage of solar-battery operation is the reduction of the acoustic signature. In tactical scenarios, the reduction of noise produced by generators can contribute to plant discretion and decrease logistical vulnerability. In addition, remote monitoring allows the monitoring of the status of the system by specialized personnel without a permanent presence near the platform.

7. CASE STUDY: HIGH-LOAD OPERATION WITHOUT PHOTOVOLTAIC PRODUCTION

On April 7, a functional test of the MAES system was carried out by connecting a three-phase load of approximately 11 kW. The scenario aimed to evaluate the behavior of the system in conditions of lack of photovoltaic production, without power from the grid and without starting the generator. Therefore, the load was supported exclusively from the $LiFePO_4$ battery bank, via the system's three-phase inverters.

For graphical representation, the time values were adjusted to ensure consistency between the experimental description and the figures.

Table 3. Extracted operating values during the high-load MAES case study

Analysis time	AC Load (kW)	Battery SOC (%)	Battery Power (kW)	PV Power (W)	Relevant observations
17:55	11.27	86.4	-12.1	0	L1: 3713 W; L2: 3799 W; L3: 3755 W
18:00	11.00	84.0	-12.0	0	Shore disconnected; generator stopped
18:24	11.18	72.1	-12.1	0	L1: 3711 W; L2: 3744 W; L3: 3725 W
19:59	11.17	23.8	-12.1	0	L1: 3730 W; L2: 3732 W; L3: 3711 W
20:25	-	12.0	-	-	Low SOC alarm

The data extracted from Table 3 shows that the AC load remained almost constant, between 11.17 kW and 11.27 kW, with a balanced distribution on the three phases. The power extracted from the batteries was approximately 12.1 kW, at a voltage of about 51-52 V and a discharge current of approximately 232-237 A. The difference between the DC power extracted from the batteries and the AC power delivered to the load is explained by the conversion efficiency, internal losses and auxiliary consumption of the system.

The evolution of the state of charge is significant. The battery's SOC decreased from 86.4% at the 5:55 p.m. analysis time to 23.8% at the 7:59 p.m. analysis time, and the system subsequently generated a Low SOC alarm at 12% around the 8:25 p.m. analysis time. The result confirms the ability of MAES to sustain a high three-phase load for about two and a half hours, with no solar input, no grid and no generator.

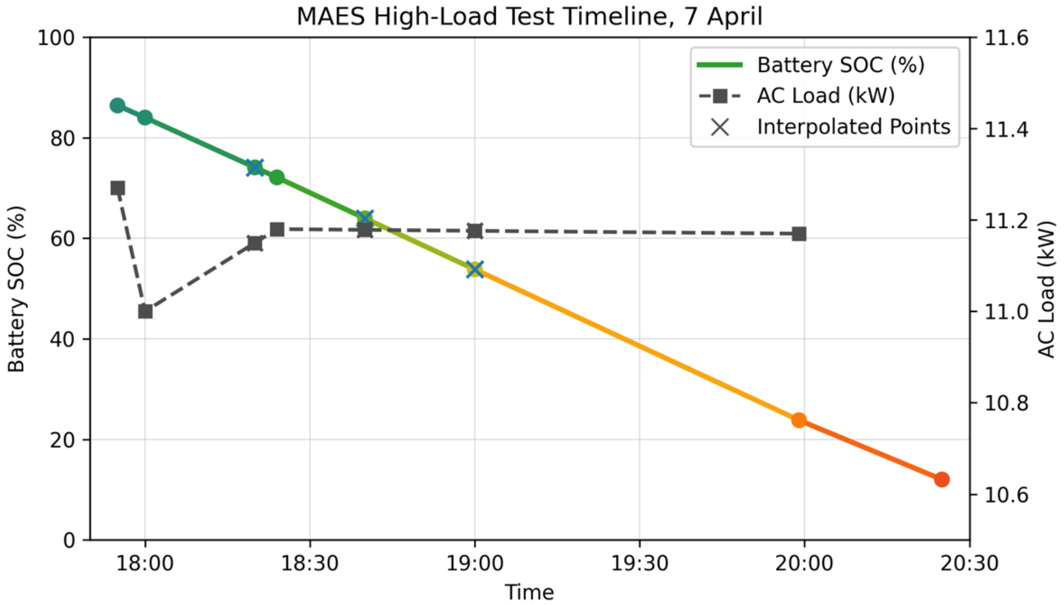

FIG. 4 MAES high-load test timeline, 7 April

Figure 4 graphically represents the evolution of the SOC and AC load during the test. The SOC curve is represented gradually, with blue for high values, then green, yellow, orange, and red for low values. The intermediate values at 18:20, 18:40 and 19:00 will be marked as interpolated values, obtained by linear interpolation between the measured points.

The case study should not be interpreted as a complete system qualification test, but as a preliminary, operationally and educationally relevant experimental validation. From a didactic perspective, it provides a real dataset for autonomy calculation, phase balancing analysis, conversion efficiency evaluation and BMS alarm interpretation. From an operational perspective, it demonstrates that the MAES can sustain large loads in the absence of photovoltaic production, with real-time monitoring of the remaining autonomy.

The simplified relationship between the available useful energy and the average load power can be used to estimate the range. This relationship does not include all the actual factors, but it is sufficient for preliminary operational planning. In practice, the actual autonomy is influenced by the battery temperature, the efficiency of the inverters, the auxiliary consumption, the load profile and the protection thresholds imposed by the BMS.

Table 4. Simplified autonomy estimation for different AC load levels

AC Load (kW)	Ideal autonomy using 40.96 kWh (h)	Practical autonomy using 80% usable energy (h)
5	8.2	6.6
10	4.1	3.3
11	3.7	3.0
15	2.7	2.2
20	2.0	1.6
25	1.6	1.3

8. DISCUSSIONS

The results presented indicate that the MAES has a double value: educational platform and tactical energy support tool. The educational character is essential, as the system allows the formation of interdisciplinary skills at the intersection of energy, power electronics, automation, communications, radiolocation and operational management. Students can understand through experiment how an energy infrastructure supports the operation of modern military systems. Educationally, the value of the MAES is at least as important as the operational value. Students do not only work with diagrams or simulations, but with a real system, which allows measurements, interpretations and decisions. Range estimation errors, conversion losses, phase imbalances, the effect of temperature on the battery, the variation in solar production and the system's response to dynamic loads can be analyzed. This approach supports the formation of a professional profile adapted to the technical requirements of the modern Air Force.

From an operational point of view, the MAES should not be considered as an absolute substitute for generator sets, but as a hybrid system capable of reducing dependence on them. The use of photovoltaics and batteries allows to reduce fuel consumption, reduce noise and increase energy flexibility. At the same time, the existence of the generator and the possibility of connecting to the grid retains the necessary redundancy for long scenarios or for loads beyond the capacity of the storage system.

There are also limitations that need to be mentioned. Photovoltaic production depends on the season, time, orientation, angle of inclination and weather conditions. The battery capacity, while significant for a mobile platform, cannot support large loads indefinitely. Remote monitoring also depends on connectivity, and field use requires clear installation, grounding, mounting, wind protection, and safety management procedures. These limitations do not reduce the value of the platform, but indicate the necessary directions for further testing, optimization, and development.

Table 5. Advantages and limitations of the MAES prototype

Advantages	Limitations
Reduced dependence on diesel generator operation	PV production depends on irradiance and weather conditions
Low acoustic signature during battery operation	Autonomy decreases rapidly under high continuous loads
Three-phase off-grid power supply	Requires careful load and energy management
Remote monitoring and real-time supervision	Remote access depends on communication coverage
Dual operational and educational value	Long-term field validation is still required

The main limitations are related to the dependence of solar production on weather conditions, autonomy limited to continuous high loads and the need for clear energy management procedures.

In the case of a load of about 11 kW, the case study shows an autonomy of the order of hours in the absence of solar input. For longer missions, the MAES must be operated in hybrid mode, combining solar production, storage, generator and possibly external sources.

From the perspective of future developments, the platform can be extended by integrating additional modules, by connecting several units in parallel, by developing autonomy prediction algorithms and by correlating energy data with the real consumption profiles of tactical systems. Another direction is integration with digital training systems so that MAES data can be used in laboratories, simulations and applied exercises.

CONCLUSIONS

MAES demonstrates the feasibility of integrating photovoltaic generation, $LiFePO_4$ storage, three-phase off-grid conversion, automatic transfer between sources and remote monitoring in a mobile platform with relevance for education, research and tactical energy support. The main contribution of the system is that it transforms energy autonomy into an object of applied study and a testable operational capability.

The paper first dealt with the use of MAES as a teaching and research laboratory, then the power supply of a mobile command post and the energy support for communication systems and applications associated with radiolocation. This approach reflects the Air Force Academy's role in training specialists capable of understanding both the technical mission systems and the energy infrastructures that support them.

The case study carried out with a three-phase load of about 11 kW, in the absence of photovoltaic production, confirms the system's ability to operate autonomously based on stored energy. Controlled SOC decrement, AC load stability, and real-time monitoring support the idea that MAES can be used both as a training platform and as a solution to increase energy resilience in realistic tactical scenarios.

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REFERENCES

[1] L. Găină, The Mobile Module for Ensuring Energy Autonomy from Sustainable Sources (MAES), Review of the Air Force Academy, no. 2(50), 2024;
[2] E. L. Miron and L. Gherman, A New Age in the Air Force: The Digitalization of Military Higher Education, Scientific Research and Education in the Air Force - AFASES 2022, pp. 99-102, DOI: 10.19062/2247-3173.2022.23.14;
[3] E. L. Miron, D. Nagy, L. Gherman and M. Marinov, Systems for Aerial Surveillance and Security - A Step Forward for Air Force Academies, Scientific Journal of Silesian University of Technology. Series Transport, vol. 106, pp. 123-130, 2020;
[4] M. A. Meclea, A. M. Baldea and M. Boscoianu, Aspects Regarding the Post-Covid Digitalisation of Military Higher Education, EDULEARN24 Proceedings, pp. 9675-9680, 2024, DOI: 10.21125/edulearn.2024.2330;
[5] S. D. Pohrib, A. S. Goga and A. Pîslă, Smart ERP Systems - From Data to Decisions, Proceedings of the International Conference on Business Excellence, vol. 19, no. 1, pp. 380-401, 2025, DOI: 10.2478/picbe-2025-0032;

[6] A. D. Deliu, E. Cazacu, F. Deliu, C. Popa, N. S. Popa and M. Preda, Dynamic Average-Value Modeling and Stability of Shipboard PV-Battery Converters with Curve-Scanning Global MPPT, Electricity, vol. 6, no. 4, 66, 2025;
[7] O. Cristea, N. S. Popa, M. G. Manea and C. Popa, About the Automation of an Autonomous Sail-propelled Search Drone, Engineering, Technology & Applied Science Research, vol. 13, no. 6, pp. 12334-12341, 2023;
[8] "Henri Coandă" Air Force Academy, MMAAESS Specifications - Mobile Module for Ensuring Energy Autonomy from Sustainable Sources, internal document PSCD 2024, Brașov, 2024;
[9] *** Victron Energy, Technical documentation: Quattro 48/10000/140-100/100, SmartSolar MPPT, Lynx Smart BMS NG, Lynx Distributor, Lithium NG batteries, EV Charging Station and Cerbo GX, 2024;
[10] *** Trina Solar, Vertex S+ TSM-NEG9R.28 Dual Glass N type i-TOPCon Module, Datasheet, 2023;
[11] *** Könner & Söhnen, Diesel Generator KS 9300DE-1/3 ATSR - Technical Manual and Operating Instructions, DIMAX International GmbH, 2024;
[12] C. Cioacă, V. F. Popescu, V. Prisacariu, S. Pop and C. Vidan, UAS Flexible Configuration for Optimum Performance in ISTAR Military Missions, Studies in Informatics and Control, vol. 31, no. 3, pp. 117-124, 2022;
[13] A. Sârbu, D. Alexandrescu and C. Galben, Prospects of Troposcatter Systems in Military Communication Networks, International Conference Knowledge-Based Organization, vol. 31, no. 3, 2025;
[14] V. Rusu and G. Calefariu, Definition and Literature Review on Human Performance Envelope Concept in Aerospace Activity, RECENT Journal, vol. 22, no. 1, pp. 41-49, 2021, DOI: 10.31926/RECENT.2021.63.041;
[15] F. A. Sârbu and R. G. Țicușan, Research on the Concept of Antifragility in Project Management Applied in Industry 4.0, RECENT Journal, vol. 22, no. 3, pp. 145-150, 2021, DOI: 10.31926/RECENT.2021.65.145.