Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 125 **2024**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2024.125.12

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Marcisz, M., Kozuba, J., Ulman, K. Development directions of energy sources for unmanned aerial vehicle (UAV). *Scientific Journal of Silesian University of Technology. Series Transport*. 2024, **125**, 177-189. ISSN: 0209-3324.
DOI: https://doi.org/10.20858/sjsutst.2024.125.12.

Marek MARCISZ[1], Jarosław KOZUBA[2], Kamil ULMAN[3]

DEVELOPMENT DIRECTIONS OF ENERGY SOURCES FOR UNMANNED AERIAL VEHICLE (UAV)

Summary. The aim of the research was to conduct a comprehensive analysis of various energy sources used in unmanned aerial vehicles (UAVs) and to determine which implemented energy sources are the best as well as what are the directions of energy source development. One hundred drone models were selected for the study, differing in their installed energy source, flight time, payload capacity, own weight, and application. The analyzed UAVs were powered by 6 energy sources: lithium polymer and lithium-ion batteries, combustion engines, hybrid drives, hydrogen fuel cells, and solar energy. The analysis covered both technical and economic, environmental, and operational aspects influencing the choice of a specific energy source. It allowed determining the best energy source for each of the 4 selected applications: military, monitoring, transport, and agriculture. An assessment of challenges related to the use and development of energy sources was also carried out, and areas where further research and innovation are necessary and essential were identified. It was found that in military applications, the development of UAV energy sources will focus on combustion engines and electric propulsion with

[1] Faculty of Transport and Aviation Engineering, The Silesian University of Technology, Krasińskiego 8 Street, 40-019 Katowice, Poland. Email: marek.marcisz@polsl.pl. ORCID: https://orcid.org/0000-0002-8178-880X
[2] Faculty of Transport and Aviation Engineering, The Silesian University of Technology, Krasińskiego 8 Street, 40-019 Katowice, Poland. Email: jaroslaw.kozuba@polsl.pl. ORCID: https://orcid.org/0000-0003-3394-4270
[3] Faculty of Transport and Aviation Engineering, The Silesian University of Technology, Krasińskiego 8 Street, 40-019 Katowice, Poland. Email: kamiulm332@student.polsl.pl. ORCID: https://orcid.org/009-0003-5050-6018

lithium polymer batteries. In civilian applications (in transport, monitoring, and agriculture), it will be directed towards further research and improvement of hybrid drives and hydrogen fuel cells.

Keywords: unmanned aerial vehicles, energy sources, lithium polymer batteries, hybrid drives, hydrogen fuel cells, solar energy

1. INTRODUCTION

The market for unmanned aerial vehicles (UAVs or drones) is developing rapidly and in an extremely dynamic manner, driven by their increasing popularity. It is one of the fastest-growing areas of technology, representing one of the most important and promising areas of aerospace engineering development. In a rapidly evolving world, technological progress has enabled the development of unmanned systems, and the demand for UAVs and their scope of application continues to grow, making them standard research platforms that have reached a level of practical reliability and functionality. The utilization of advanced emerging technologies, such as unmanned aerial systems, undoubtedly provides an alternative to traditional methods widely used in various industries and sectors of the economy. Since their introduction to the market, UAVs have revolutionized many fields and find application in all kinds of unconventional tasks. Often, their use proves to be the only method of measurement, especially in cases where human intervention entails high risk or is simply impossible [9]. However, in all of these undeniably significant possibilities for drone usage, there arises a considerably limiting factor: their operational time and associated range, and subsequently, their operational scope. Therefore, one of the key challenges facing the development of unmanned aviation technologies is the issue of energy sources implemented on drones, which directly affects the value of the aforementioned parameters. Contemporary UAVs are equipped with various energy sources, including lithium polymer batteries (Li-Po), lithium-ion batteries (Li-Ion), combustion engines (gasoline, turboprop, diesel, and turbojet), hybrid technologies (hybrid fuel cells: two-stroke engine + Li-Po batteries), hydrogen fuel cells, solar panels, or even technologies allowing drones to be charged using lasers from very long distances. Therefore, choosing the right energy source is crucial to achieve optimal performance, flight time, and drone range, and growing expectations in this regard necessitate continuous development and optimization of existing technologies as well as the search for new, innovative solutions in the field of energy sources for UAVs. The aim of the research was to analyze various energy sources used in unmanned aerial vehicles (UAVs) and to identify challenges associated with their utilization and development, as well as to identify areas where further research and innovations are necessary. A detailed analysis of the advantages and limitations of each energy source provided comprehensive knowledge on the selection and optimization of energy sources in UAVs, thereby supporting engineers and designers in creating more efficient and sustainable solutions for the future of unmanned aviation.

2. ENERGY REQUIREMENTS AND TYPES OF ENERGY SOURCES IN UAV

Unmanned aerial vehicles consume significant amounts of energy to sustain flight, making the selection of the appropriate energy source one of the most crucial aspects of drone technology. An ideal energy source should be characterized by: low weight, high nominal capacity or high calorific value, ease, and speed of replacing depleted cells/fuel, resistance to variable atmospheric conditions, and relatively low cost. Providing a clear indication of an energy source that can simultaneously fulfill all the aforementioned characteristics is nearly impossible. Therefore, there is a need for compromise to determine which of these characteristics is most crucial. The efficiency of an energy source also depends on factors related to the construction of the drone, the propulsion system used, as well as the flight time. The primary factors influencing energy consumption in unmanned aerial vehicles include: mass and aerodynamics, construction and type of propulsion system (multirotor or fixed-wing with a design similar to an airplane), batteries and energy storage methods, control systems, and flight environment. The energy requirements of UAVs also define their purpose in terms of utilization across various industries and sectors of the economy. Drones were originally intended primarily for military use. It was only much later that they began to be slowly introduced for civilian use. Military applications of drones mainly include: troop protection (such as gathering information using methods like "hover and stare" or "perch and stare"), mine detection, transport (moving goods within and beyond the battlefield), artillery support (accurate and swift enemy position locating), special forces operations support (a crucial element of reconnaissance and intelligence), and strike missions. Solutions used in military UAVs are often adapted in drone models for civilian use. In everyday life, drones find their widest application in various forms of monitoring (including inspection), transport, and agriculture (primarily in precision agriculture). The drone market offers various power sources for UAVs, where the value of most of them is determined by power density (referring to the amount of energy the source can deliver at a given moment) and energy density (referring to the energy that can be stored in the source, i.e., how long such an amount of energy can be supplied), as illustrated by the Ragone plot (Fig. 1) [1].

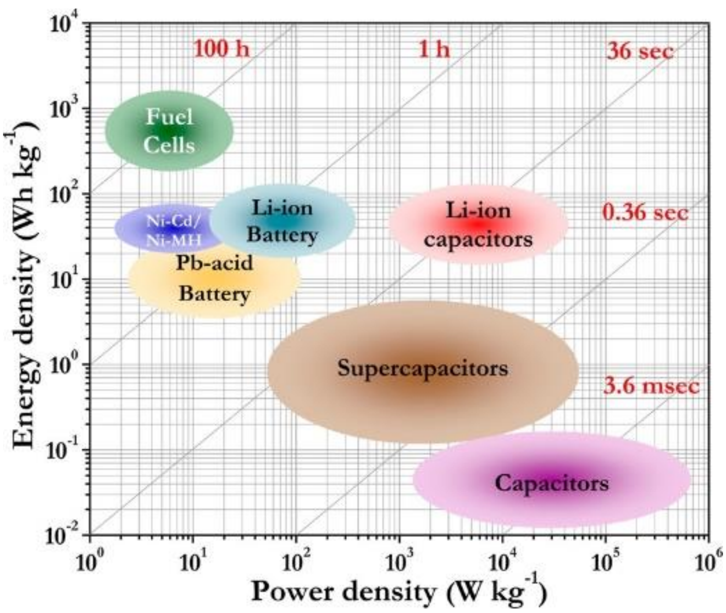


Fig. 1. Ragone plot [1]

During the conducted research, some of the sources were rejected due to their excessive own weight, excessive size (limiting operational capabilities), or insufficient energy capacity. Given the mentioned characteristics, particular attention, in the form of energy sources for UAVs, deserves:

- batteries (along with all their advantages, but also drawbacks): lead-acid (Pb-Acid), nickel-cadmium (NiCad), nickel-metal-hydride (NiMH), alkaline, lithium-polymer (Li-Po), lithium-ion (Li-Ion), zinc-air ($Zn-O_2$), lithium-air (Li-Air), lithium-thionyl chloride ($Li-SOCl_2$) [3, 8, 9, 12];
- internal combustion engines: piston, turbine, jet;
- hybrid drives, constituting a complex combination of the benefits of combustion and electric propulsion, while simultaneously eliminating their unfavorable characteristics [5, 12];
- fuel cells (FC), serving as a form of alternative energy sources: Alkaline FC (AFC), Proton Exchange Membrane (PEMFC), Phosphoric Acid FC (PAFC), High-Temperature FC (HTFC) [2, 4, 6, 9-12];
- solar cells, based on two technologies: PV system (utilizing the photovoltaic effect, involving the direct conversion of solar radiation) or CSP system (based on concentrated solar power, using water vapor to drive turbines generating electricity) [7].

3. METHOD

The research was conducted based on a comparison of 100 selected drone models, differing in their implemented energy source, maximum flight time, maximum payload, own weight, and application (Tab. 1).

Tab. 1

Characteristics of the analyzed UAV models

No.	Model	Energy source	Time of flight [min]	Weight [kg]	Payload [kg]	Application
1	Autel Evo Nano +	Li-Polymer	28	0,249	0	monitoring
2	Parrot Anafi SE	Li-Polymer	32	0,5	0	monitoring
3	SG V100	Li-Polymer	180	10	5	monitoring
4	Fixar 007	Li-Polymer	60	5	2	monitoring
5	L10 Pro	Li-Polymer	26	18,3	10,7	agriculture
6	XAG P100	Li-Polymer	17	51,5	40	agriculture
7	PH-20	Li-Polymer	70	19,2	10	transport
8	SG M300	Li-Polymer	80	10,7	8	transport
9	SG M600	Li-Polymer	60	23	22	transport
10	Bayraktar Mini	Li-Polymer	120	4,5	0	military
11	DeltaQuad Pro	Li-Polymer	110	5	1,2	military
12	Eleron 3	Li-Polymer	90	4,5	1	military
13	EOS C-VTOL Magyla	Li-Polymer	180	14,2	1,1	military
14	FlyEye	Li-Polymer	240	12	0	military
15	Lastochka-M	Li-Polymer	120	5,3	0,35	military
16	Leleka-100	Li-Polymer	210	6	0	military
17	Malloy T150	Li-Polymer	36	120	68	military
18	Puma	Li-Polymer	330	10,7	2,5	military

19	Punisher	Li-Polymer	90	6,5	3	military
20	R-18	Li-Polymer	30	25	5	military
21	Revolver 860	Li-Polymer	20	31,5	10,5	military
22	Switchblade 600	Li-Polymer	40	15	2,3	military
23	Vector	Li-Polymer	180	8,5	0	military
24	Warmate	Li-Polymer	50	4	1	military
25	Xdynamics-Evolve	Li-Polymer	33	2	0	military
26	ZALA KYB	Li-Polymer	30	3	0	military
27	ZALA Lancet-3	Li-Polymer	60	7	5	military
28	ZALA-421	Li-Polymer	90	1,4	1	military
29	Matrice 600 Pro	Li-Polymer	35	10	6	monitoring
30	Falcon 8+	Li-Polymer	18	1,2	0,8	monitoring
31	Matrice 300 RTK	Li-Polymer	55	6,3	2,5	monitoring
32	Agras T30	Li-Polymer	60	37	30	agriculture
33	Mavic 3 Pro	Li-Ion	43	0,958	0	monitoring
34	Inspire 3	Li-Ion	28	4	0,38	monitoring
35	Matrice 350 RTK	Li-Ion	55	6,47	0,96	monitoring
36	Mavic 3 Classic	Li-Ion	46	0,895	0	monitoring
37	Air 3	Li-Ion	46	0,72	0	monitoring
38	Avata	Li-Ion	18	0,41	0	monitoring
39	Agras T10	Li-Ion	60	16	10	agriculture
40	UAS A1-CM Furia	Li-Ion	180	5,5	0	military
41	CW-25	hybrid	360	30	6	monitoring
42	CW-80E	hybrid	480	80	20	monitoring
43	GAIA 160HY	hybrid	180	15,5	3	monitoring
44	H2	hybrid	300	17	5	monitoring
45	HAVELSAN BAHA	hybrid	360	13	5	monitoring
46	Hybrix 2.1	hybrid	240	13	5	monitoring
47	Hydra-400	hybrid	330	50	120	monitoring
48	NOA Hybrid	hybrid	175	25	6	monitoring
49	HF T60-H	hybrid	60	60	60	agriculture
50	Perimeter 8	hybrid	300	16	10	agriculture
51	UAS-25g	hybrid	25	34	26	agriculture
52	UAS-CTH	hybrid	30	27,8	32,8	agriculture
53	Drone Volt Heliplane LRS 340	hybrid	210	15	3	monitoring
54	Anavia HT-100	hybrid	250	55	65	transport
55	LHD	hybrid	360	110	100	transport
56	SG V900	hybrid	210	60	40	transport
57	X55	hybrid	180	8,6	7,7	transport
58	XER X8 Heavy	hybrid	210	25	7	transport
59	YD6-1600L	hybrid	120	26,6	6,5	transport
60	Yeair	hybrid	60	5	5	transport

61	H6 Poseidon II	hybrid	420	75	25	military
62	Lemur	hybrid	480	20	5	military
63	Merlin-VR	hybrid	600	47	6,5	military
64	PW-Zoom	combustion engine	60	22	2	monitoring
65	UAS6-50g	combustion engine	120	100	50	agriculture
66	CASC Rainbow-4	combustion engine	360	40	4,5	military
67	Elbit Hermes 900	combustion engine	2160	670	300	military
68	General Atomics Avenger	combustion engine	1080	5355	2900	military
69	IAI Eitan	combustion engine	1800	2700	2700	military
70	MQ-1 Predator	combustion engine	2040	512	386	military
71	Scrab I	combustion engine	30	28	4	military
72	PD-2	combustion engine	600	16	3	military
73	Forpost-R	combustion engine	1200	330	120	military
74	Korsar	combustion engine	600	160	40	military
75	Mohajer-6	combustion engine	720	520	150	military
76	MQ-Reaper	combustion engine	1680	2220	1360	military
77	Orion	combustion engine	1440	650	450	military
78	Orlan-10	combustion engine	960	18	6	military
79	Shahed 129	combustion engine	1440	400	132	military
80	Shahed-136	combustion engine	690	150	50	military
81	Ukrjet Uj-22	combustion engine	420	50	20	military
82	Bayraktar TB2	combustion engine	1620	595	55	military
83	ANNA	hydrogen FC	60	11	5	monitoring
84	Dodeca	hydrogen FC	300	24	3	monitoring
85	DS30W Specs	hydrogen FC	120	22	3	monitoring
86	H100	hydrogen FC	55	55	30	monitoring
87	H2D200	hydrogen FC	240	15	4,5	monitoring

88	H2D250	hydrogen FC	480	40	10	monitoring
89	H2D55	hydrogen FC	100	30	7	monitoring
90	Hexa	hydrogen FC	360	20	3	monitoring
91	BSHARK	hydrogen FC	120	8	1	monitoring
92	Hydrone 1550	hydrogen FC	150	16,5	2	monitoring
93	Urban	hydrogen FC	37	15	10	transport
94	Tachyon	hydrogen FC	120	20	5	military
95	Aero Vironment Pathfinder	solar panels	720	250	45	monitoring
96	BAE Systems PHASA-35	solar panels	4320	150	15	monitoring
97	Qimingxing-50	solar panels	259200	19	0	monitoring
98	UAVOS ApusDuo	solar panels	525600	43	2	monitoring
99	UK OS Astigan A3	solar panels	129600	149	25	monitoring
100	Zephyr 8/S	solar panels	37440	65	5	monitoring

In the analysis of energy sources used in UAVs, four parameters of drones were taken into account as outlined in Tab. 1, with the respective divisions:

- energy source, with distinction: lithium-polymer batteries (Li-Pol), lithium-ion batteries (Li-Ion), hybrid drives, combustion engines, hydrogen fuel cells, and solar panels;
- maximum flight time, with distinction of the most common time intervals in drone operations: up to 60 minutes, from 61 to 180 minutes, from 181 to 360 minutes, from 361 to 600 minutes, and above 600 minutes;
- drone's own weight, according to the classification into classes based on the new EASA regulations for UAV classification, effective from January 1, 2024: C0 up to 0.250 kg, C1 up to 0.9 kg, C2 up to 4 kg, C3/C4 up to 25 kg, C5/C6 up to 25 kg (differs from class C3/C4 with additional requirements such as land mode, low-speed mode, telemetry), above 25 kg;
- maximum payload, with distinction of the most commonly used categories: up to 5 kg, from 5 to 10 kg, above 10 kg;
- application, divided into four main groups of drone applications: military, monitoring, transport, and agriculture.

4. RESULTS

Based on the conducted analysis (Tab. 1), it can be concluded that drones with lithium-polymer batteries are characterized by a short flight time, low payload capacity, light weight, and are intended for military and monitoring purposes (Fig. 2).

Drones powered by lithium-ion batteries are characterized by short flight time, low weight, and low payload capacity, with the majority of them finding application in the commercial market for monitoring purposes (Tab. 1, Fig. 3).

UAVs with hybrid propulsion systems are characterized by long flight times, large weight, and have varied payload capacities, adapting to the tasks for which they are utilized. They find application in every industry that utilizes drones (Tab. 1, Fig. 4).

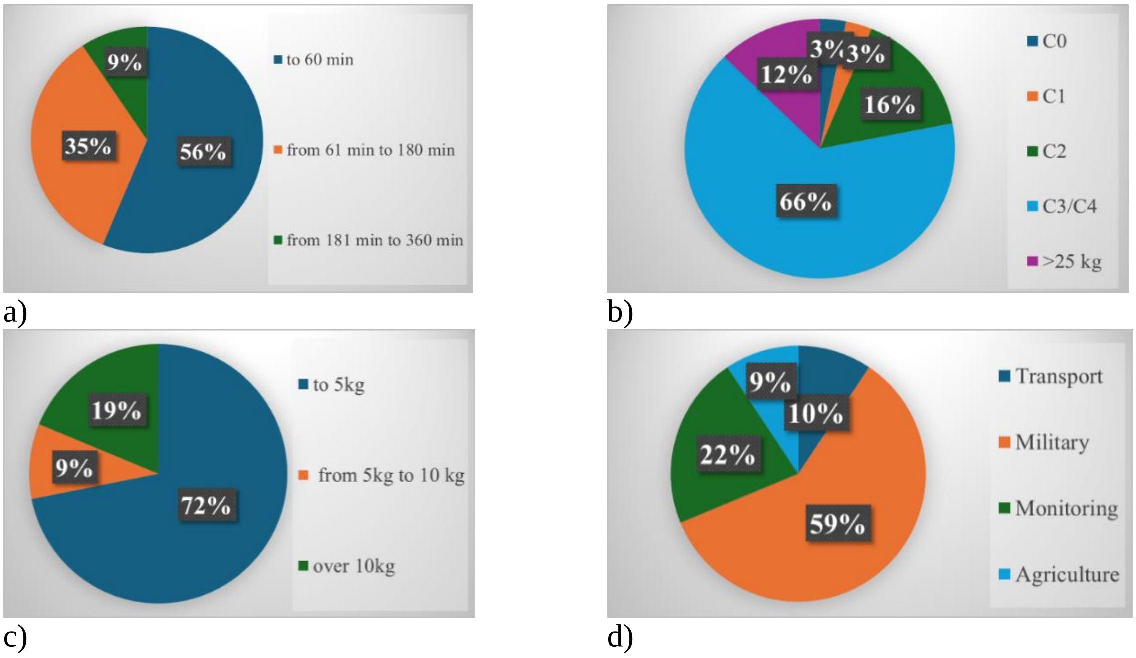


Fig. 2. Percentage distribution of drones powered by Li-Po batteries based on: maximum flight time (a), own weight (b), maximum payload (c), and application (d)

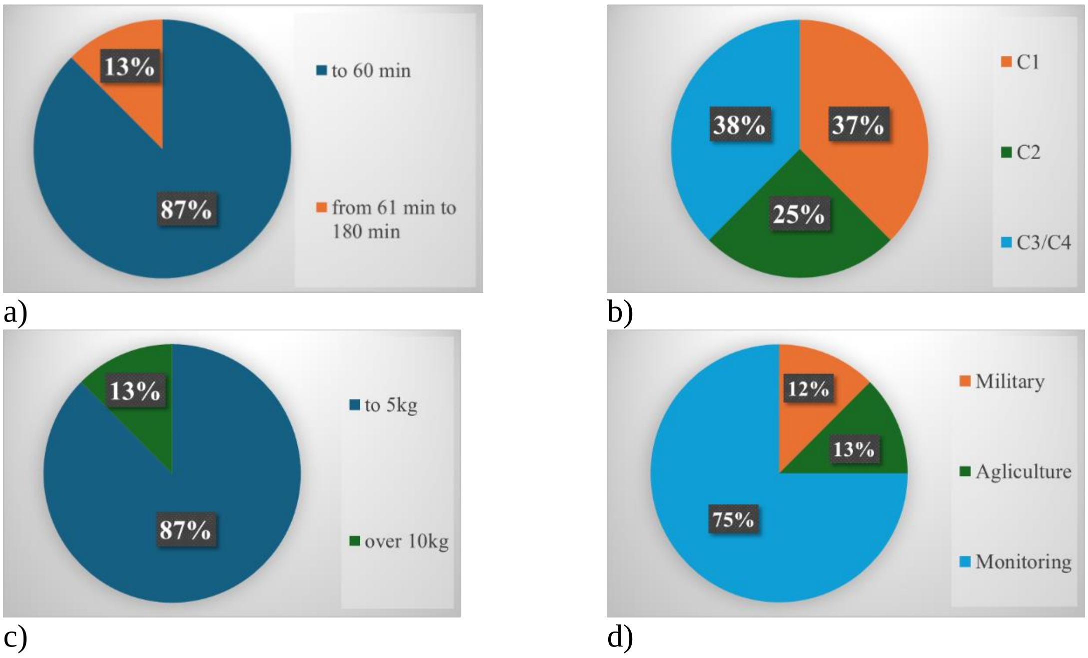
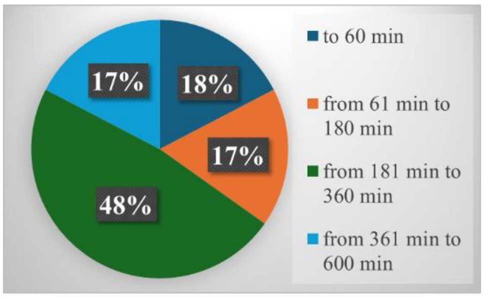
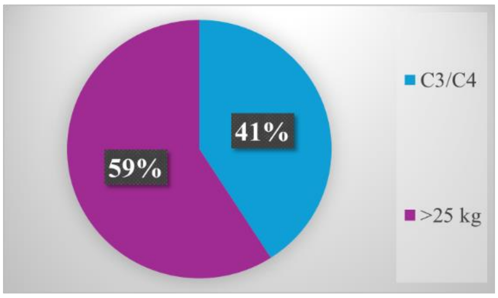


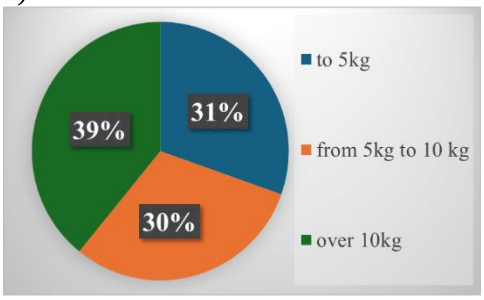
Fig. 3. Percentage distribution of drones powered by Li-Ion batteries based on: maximum flight time (a), own weight (b), maximum payload (c), and application (d)



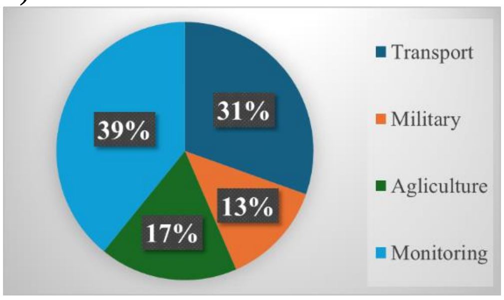
a)



b)



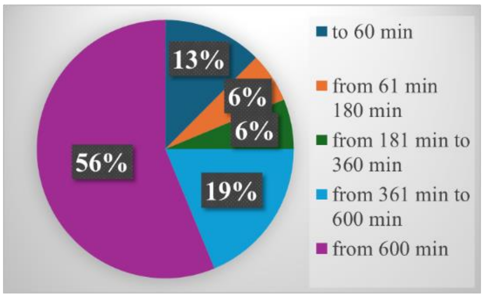
c)



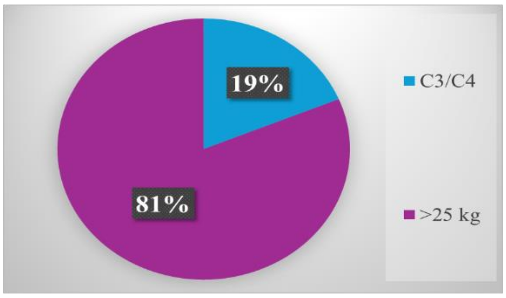
d)

Fig. 4. Percentage distribution of drones powered by hybrid drives based on: maximum flight time (a), own weight (b), maximum payload (c), and application (d)

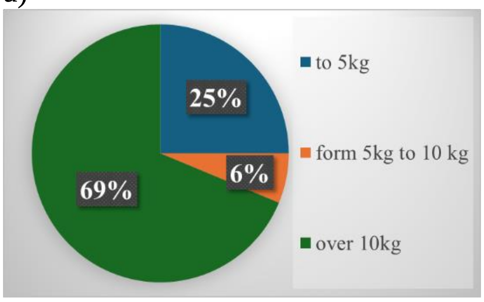
UAVs with combustion engine propulsion systems are characterized by very long flight times, large weight, and high payload capacity, making them widely used in the military as the weapon of the 21st century (Tab. 1, Fig. 5).



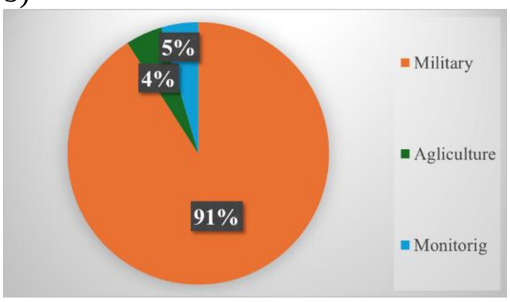
a)



b)



c)



d)

Fig. 5. Percentage distribution of drones powered by combustion engine based on: maximum flight time (a), own weight (b), maximum payload (c), and application (d)

The majority of drones powered by hydrogen fuel cells are characterized by a flight time of up to 180 minutes. They typically exhibit a weight not exceeding 25 kg. The payload capacity of these machines is relatively small, usually up to 5 kg. Most UAVs powered by hydrogen fuel cells are used in industries related to various forms of monitoring (Tab. 1, Fig. 6).

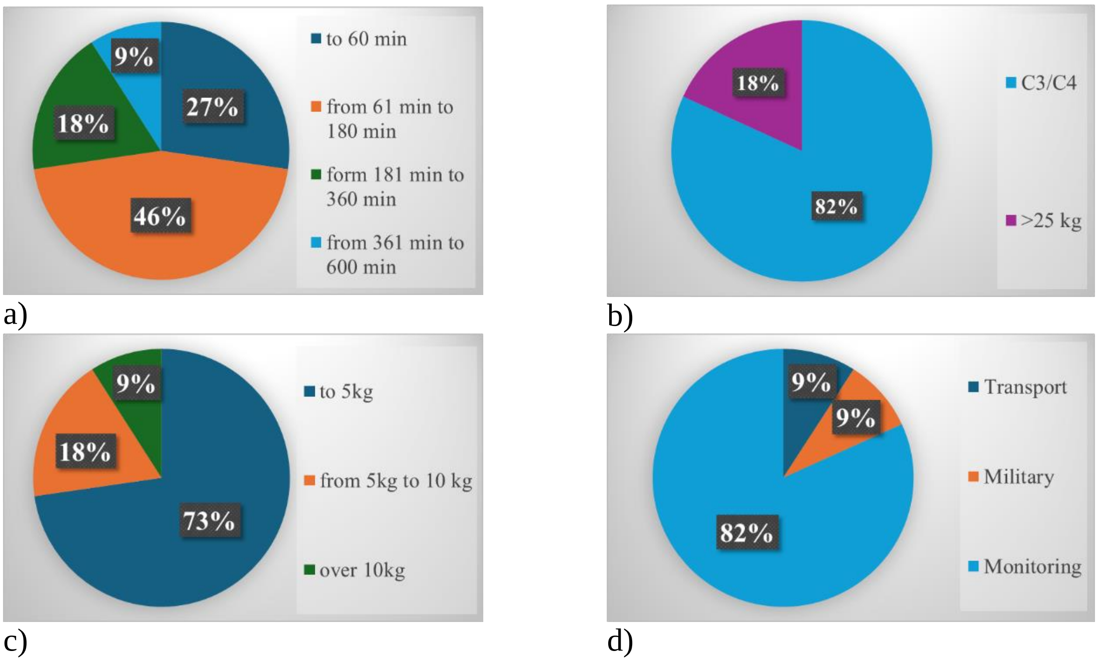


Fig. 6. Percentage distribution of drones powered by hydrogen fuel cells based on: maximum flight time (a), own weight (b), maximum payload (c), and application (d)

UAVs powered by solar panels are characterized by a flight time exceeding 600 minutes. Manufacturers of these drones often present the values of this parameter in days or even months, illustrating the extent of their range. Unfortunately, they must be constantly powered by solar panels, which requires operating at high altitudes. These features of such UAVs primarily find their application in monitoring, often playing the role of “satellites”. The weight of these UAVs is mostly above 25 kg, and their payload does not exceed 10 kg (Tab. 1, Fig. 7).

In the industries under analysis, most military drones utilize a combination of two energy sources: electric propulsion with lithium-polymer batteries and combustion propulsion. This choice is influenced by the specific requirements of military operations and the varied tasks assigned to drones in this sector. On the other hand, drones used for monitoring and inspection tasks draw their energy primarily from three sources: hydrogen fuel cells, hybrid drives, and electric drives with lithium-polymer batteries. Hybrid propulsion systems are favored in transport drones to handle their substantial payload capacity, while agricultural drones also opt for hybrid systems due to their need for robust payload capacity.

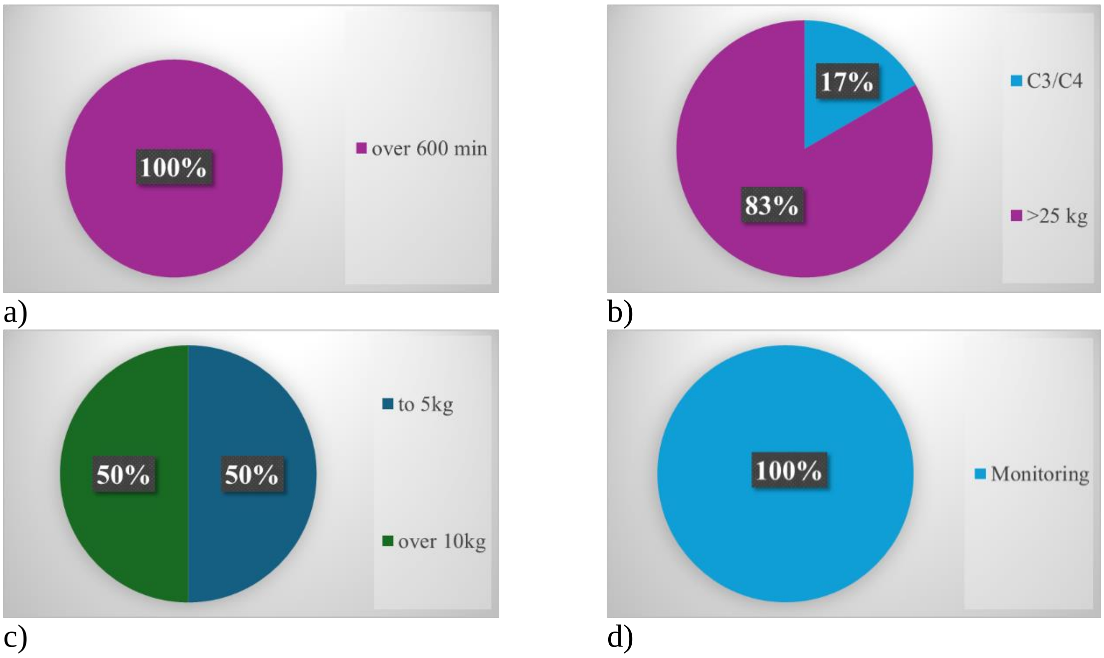


Fig. 6. Percentage distribution of drones powered by solar panels based on: maximum flight time (a), own weight (b), maximum payload (c), and application (d)

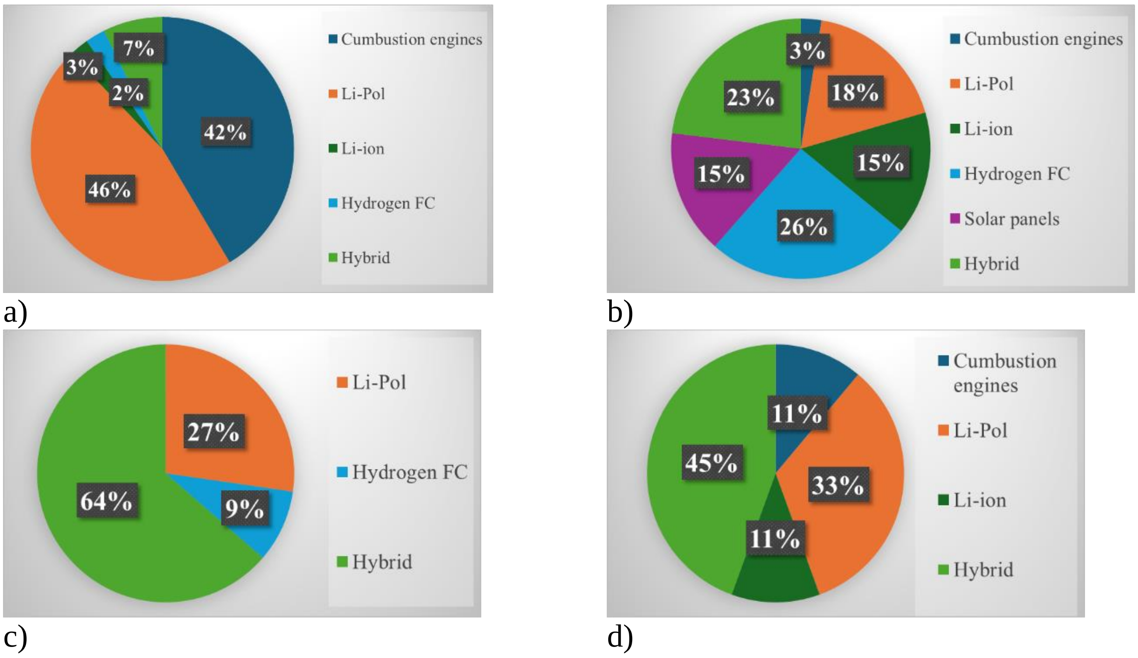


Fig. 7. Percentage distribution of drones based on their application in: military (a), monitoring (b), transport (c), agriculture (d)

5. CONCLUSION

The conducted research has provided answers to questions regarding the challenges associated with the development of UAV energy sources and their utilization. The results of the research have shown which aspects need to be considered in selecting the energy source implemented in UAVs to most effectively carry out their assigned tasks. The analysis allowed for presenting the energy requirements of UAVs and indicating the directions in which development and further research will progress, aiming to create the ideal and universal energy source. Based on the conducted research, it can be concluded that in military applications, the direction of UAV energy source development will move towards drones with combustion and electric propulsion systems using lithium-polymer batteries. In civilian applications, mainly involving monitoring, transport, and agriculture, further research and improvement of UAV propulsion systems will focus on hybrid drives and fuel cells.

References

1. Aravindan Vanchiappan, Joe Gnanaraj, Yun-Sung Lee, Srinivasan Madhavi, 2014. „Insertion-type electrodes for nonaqueous Li-ion capacitors”. *Chemical Reviews* 114(23):11619-35. DOI: 10.1021/cr5000915.
2. Barreras Toledo Félix, Antonio Lozano Fantoba, Luis Valiño García, Carlos Marín Hernández, Antonio Pascau, 2005. „Flow distribution in a bipolar plate of a PEM fuel cell: experiments and numerical simulation studies”. *Journal of Power Sources* 144(1): 54-66. DOI: 10.1016/j.jpowsour.2004.11.066.
3. Ci Song, Ni Lin, Dalei Wu, 2016. „Reconfigurable battery techniques and systems: a survey”. *IEEE Access* 4: 1175-1189. DOI: 10.1109/ACCESS.2016.2545338.
4. Ganguly Saibal, Sonali Das, Kajari Kargupta, Dipali Bannerjee, 2012. „Optimization of performance of Phosphoric Acid Fuel Cell (PAFC) stack using reduced order model with integrated space marching and electrolyte concentration inferencing”. *Computer Aided Chemical Engineering* 31: 1010-1014. DOI: 10.1016/B978-0-444-59506-5.50033-X.
5. Gong Andrew, Rens Macneill, Dries Verstraete, Jennifer L. Palmer, 2016. „Analysis of a fuel-cell/battery /supercapacitor hybrid propulsion system for a UAV using a hardware-in-the-loop flight simulator”. In: *2018 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*: 1-17. Cincinnati, OH, USA. 12-14 July 2018.
6. Jeon Gwang-Yeon, Hong-Jun Choi, Young-Hoon Yun, In-Su Cha, Dong-Mook Kim, Jeong-Sik Choi, Jin-Ho Jung, Jeong-Phil Yoon, 2007. „PEM (Proton Exchange Membrane) fuel cell bipolar plates”. In: *2007 International Conference on Electrical Machines and Systems (ICEMS)*: 1891-1893. Seoul, Korea (South). 08-11 October 2007. DOI: 10.1109/ICEMS12746.2007.4412119.
7. Kalogirou Soteris A. 2013. *Solar Energy Engineering. Processes and Systems*. Amsterdam: Elsevier. ISBN: 978-01-239-7270-5. DOI: 10.1016/B978-0-12-374501-9.X0001-5.
8. Karden Eckhard, Servé Ploumen, Birger Fricke, Ted Miller, Kent Snyder. 2007. „Energy storage devices for future hybrid electric vehicles”. *Journal of Power Sources* 168(1): 2-11. DOI: 10.1016/j.jpowsour.2006.10.090.
9. Mehta Viral, Joyce Smith Cooper. 2003. „Review and analysis of PEM fuel cell design and manufacturing”. *Journal of Power Sources* 114(1): 32-53. DOI: 10.1016/S0378-7753(02)00542-6.

10. Mohammed Osama A., David A. Lowther, Meng H. Lean, Bassem Alhalabi. 2001 „On the creation of a generalized design optimization environment for electromagnetic devices”. *IEEE Transactions on Magnetics* 37(5): 3562-3565. DOI: 10.1109/20.952662.
11. Thanomjit Chollaphan, Yaneeporn Patcharavorachot, Amornchai Arpornwichanop. 2012. „Design and thermal analysis of a solid oxide fuel cell system integrated with ethanol steam reforming”. *Computer Aided Chemical Engineering* 20: 287-291. DOI: 10.1016/B978-0-444-59519-5.50058-7.
12. Townsend Ashleigh, Immanuel N. Jiya, Christiaan Martinson, Dmitri Bessarabov, Rupert Gouws. 2020. „A comprehensive review of energy sources for unmanned aerial vehicles, their shortfalls and opportunities for improvements”. *Heliyon* 6(11): 1-9. DOI: 10.1016/j.heliyon.2020.e05285.

Received 05.06.2024; accepted in revised form 16.08.2024