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Photovoltaic power supply potential for the autonomous operation of the Leopard 2 main battle tank

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Abstract

As part of the global energy transition, the energy systems of modern armies are also facing transformation to gain strategic advantages in terms of both operational efficiency and the stability of supply chains, as well as to reduce their environmental footprint. The aim of this study was to investigate the extent to which the power supply of the Leopard 2 main battle tank can be supplemented with photovoltaic (PV) technology. First, the energy requirements of the tank's electrical systems were explored and analyzed, with special regard to the requirements of autonomy in combat situations. The applicability of mobile PV systems was modeled based on a trailer-mounted configuration, considering the annual solar energy potential of four different geographical locations in Hungary. The results show that under optimal conditions in late spring and mid-summer, the PV system can produce approximately 32.8–34.7 kWh/day, with the highest generation window observed between 09:00 and 14:00 (CET). However, the maximum electrical load demand of the tank can reach up to 20 kW, which significantly limits the standalone use of PV energy. Although full energy autonomy is unachievable, the system can intermittently power lower-demand subsystems, such as communication or active protection modules, but only during a restricted time window. These constraints underline the need for hybrid solutions and confirm the limited battlefield applicability of PV as a primary energy source. The innovative significance of the research is given by the fact that no comprehensive study has examined the potential military applicability of PV technology in the power supply of Leopard 2 tanks so far, so the present study fills a gap in this area.

Keywords PV technology, NATO, Tank, Leopard 2 main battle tank, Active defense

1 Introduction

1.1 Global energy transition: trends and challenges

The reduction of the role of fossil fuels in the global energy system is primarily driven by the worsening effects of climate change and the need to increase the security of energy supply and its sustainability [1]. This process is dynamically transforming the future of energy management, with a focus on renewables and innovative technologies [2].



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Graphical abstract

Can Photovoltaic Technology Revolutionize Tactical Energy Supply for the Leopard 2 Main Battle Tank?

Fossil fuels have played a decisive role in global economic development since the Industrial Revolution [3]. Low-cost and easily accessible energy supply has played an essential role in the growth and development of industrialized societies [4]. However, the need to reduce dependence on fossil fuels and the environmental problems they cause make the transition to alternative energy sources increasingly urgent [5]. In spite of this, however, fossil fuels continue to be the backbone of global energy supply [6]. According to the World Energy Outlook 2024 report, the share of fossil fuels in global final energy consumption was 66% in 2023, which is expected to decrease to 55% by 2050, based on the Stated Policies Scenario (STEPS) [7]. According to the Announced Pledges Scenario (APS), this percentage could decrease to 35%, while according to the Net Zero Emissions by 2050 (NZE) scenario, this percentage could drop to 20%.

On the positive side, the share of renewable energy sources is constantly increasing, and between 2023 and 2030 the share of modern renewable energy sources in the global energy supply is projected to increase by 5% annually. The expansion of solar and wind energy capacity is particularly outstanding. Solar PV capacity will increase significantly by 2030 in all scenarios, with the NZE scenario increasing to more than three times its current value. Wind energy is also facing rapid growth, especially in China and the United States.

Some of the biggest challenges for renewables are the limitations of variable energy generation and energy storage. The transformation of the energy market and the development of storage technologies will be key factors in ensuring the stability of supply. According to the World Energy Outlook 2024, the development of energy grids is essential for the efficient integration of variable renewable energy sources. The pace of expansion of electricity grids could increase by up to 70% by 2030 compared to current values in the STEPS scenario, while in the case of NZE it could increase by more than 110% [8].

Beyond climate and sustainability considerations, recent research highlights that the vulnerability of centralized grids also represents a critical national security risk. Distributed renewable-based microgrids, particularly those powered by solar PV, have been identified as strategically valuable solutions to enhance resilience against natural

disasters, cyber-attacks, or physical disruptions. This perspective underlines that the energy transition is not only an environmental or economic necessity, but also a strategic response to the fragility of existing infrastructures [9].

Since the burning of fossil fuels is responsible for much of the greenhouse gas emissions [10], the industrial and transport sectors could greatly contribute to achieving the goal of emission reductions by the use of electric technologies [11, 12]. In turn, reducing the consumption of fossil fuels and switching to renewables has significant economic and social impacts [13, 14]. The energy transition results in increased job creation in the clean energy industry, while jobs will be lost in fossil fuel sectors [15]. Restructuring employment in the energy sector is key to the social acceptance of the clean energy transition [16]. According to the World Energy Outlook 2024 report, the number of clean energy-related jobs will increase by 2030 in all scenarios [8]. In the STEPS scenario, the number of people working in the energy sector remains stable, while in the APS and NZE scenarios, clean energy employment will increase significantly, especially in solar, wind and electric transport [8].

The success of the energy transition will depend to a large extent on technological innovations, the development of energy networks and the effectiveness of climate protection measures [17]. The transformation of the energy market will not only bring environmental benefits but also create economic opportunities while contributing to the protection of our planet [18, 19].

1.2 Military energy dependency in the 21st century, energy transition and military innovation

Modern armies also face the challenges of energy supply, as their operation and efficiency depend to a large extent on the provision of energy carriers [20]. For instance, in their work Berardi et al. (2020) introduced a Smart Hybrid Energy System (SHES) designed for deployable military camps, showing that combining PV, storage and waste heat recovery can reduce fossil fuel demand and improve energy autonomy [21]. In the execution of military operations, energy-intensive systems, such as vehicles, weapon systems and logistics infrastructure, require continuous and reliable energy sources [22]. The use of fossil fuels in military technology also means strategic vulnerability, as the disruption of supply lines can have serious consequences during military operations [23, 24]. Therefore, armies are increasingly interested in using alternative energy sources to reduce dependence on fossil fuels and increase operational efficiency [25]. The integration of new energy sources not only brings sustainability, economic and peacetime environmental (during exercises) benefits, but can also provide significant strategic advantages in modern warfare, in particular by reducing energy needs and exposure to supply chains [26]. Recent studies have highlighted that hybrid microgrid configurations—especially those integrating PV, electric energy storage, and diesel backup—require evaluation under uncertain conditions such as fluctuating weather and variable mission durations, in order to ensure robustness in both civilian and military contexts [27].

Within armies, different weapons systems require different energy sources and amounts of energy to operate [28]. Fighter jets use extremely powerful jet engines, which require a huge amount of kerosene to operate. For example, the MiG-29B uses 4860 kg of fuel per hour, and a JAS-39 Gripen 2430 kg of fuel per hour on average [29]. Warships

also consume significant amounts of energy, especially aircraft carriers and destroyers, some of which even have a nuclear main propulsion system [30]. Furthermore, armored vehicles, tanks, artillery and missile systems used in ground operations also have high energy consumption [31]. For example, a Leopard 2 main battle tank consumes about 219 L of diesel on average per 100 km on road [32]. These military vehicles require energy not only for their movement, but also for the continuous electric power supply of their individual system elements (e.g. communication systems, targeting systems and active protection systems, etc.) [33]. More efficient management of energy needs and the inclusion of alternative sources in these systems can be a significant step forward for the operational autonomy and sustainability of armies, and even military alliances, such as NATO [34].

In order to understand the context of the integration of PV technology into military systems it is indispensable to consider insights related to the intersection of energy transition and military innovation. The energy transition discourse emphasizes that sustainable energy deployment in high-demand, security-sensitive contexts depends not only on technological feasibility but also on institutional adaptability and sociotechnical integration. Prior research stresses that the success of innovations related to renewable energy requires alignment with entrenched operational, cultural, and strategic practices, particularly in fossil-fuel dependent sectors like defense [35]. This view aligns with the literature on the broader topic of energy systems, which emphasizes the inertia and path-dependency of fossil fuel infrastructures, especially in high-demand sectors such as transportation and defense [36]. Similarly, Mori et al. (2023) demonstrated through a case study of a Slovenian military site that renewable energy hubs integrating PV, wind, and hydrogen could provide near self-sufficiency for bases while supporting civilian mobility with green hydrogen [37]. Lee et al. (2022) highlighted that even decommissioned military camps can be transformed into renewable-based virtual power plants (VPPs), showing the scalability of PV integration in tactical infrastructures [38]. Further, Semenenko et al. (2024) analyzed innovative solutions for military facilities, underscoring the combined role of renewables, microgrids, and cybersecure intelligent management in ensuring autonomy and resilience [39].

Additionally, models of military innovation and strategic technology adoption underline the necessity of synchronizing emergent energy systems with tactical needs, logistical networks, and organizational structures. Existing analyses point out that disruptive technologies in defense are unlikely to gain institutional traction unless they provide measurable advantages—such as enhanced autonomy, operational redundancy, or stealth performance [40]. These perspectives form the conceptual foundation of the present study, which views PV systems not simply as energy alternatives, but as enablers of localized energy resilience and survivability in armored military platforms. This framework builds on both theoretical insights and peer-reviewed assessments of renewable energy integration in deployed and tactical environments.

1.3 NATO's strategic energy vision and technological trends

NATO, as a prominent military alliance, pays special attention to the issue of energy supply, as modern warfare is increasingly based on the use of energy-intensive technologies [41]. In order to sustainably operate the armed forces of the Member States and ensure continuous combat readiness, the Alliance is continuously improving its energy

strategies [42]. As part of this, there is an increasing emphasis on reliable and efficient energy supply, which plays a key role not only in military but also peacetime operations. NATO's aim is to keep pace with technological developments to minimize the vulnerability of supply chains and enhance the energy independence of the allied forces [43, 44].

On the one hand, the alliance is modernizing the use of conventional energy sources to improve its energy supply, while, on the other hand, it is looking for new, innovative solutions to increase efficiency [45]. Traditional technologies (such as internal combustion engines, gas turbine jet engines, etc.) continue to play an important role in the functioning of vehicles involved in military operations, but more and more research and development is being directed at increasing the efficiency of these systems [46], for example, by using models with lower fuel consumption and reduced emissions [47] (e.g. the GM E-ISV vehicle) [48]. In addition to optimizing the use of fossil fuels, NATO is also researching the possibility of integrating hybrid and alternative energy sources [49].

This approach can also be observed on the part of NATO in the air force and the navies of the member countries [50, 51]. In the case of unmanned aerial vehicles (UAVs), experiments are underway with solar wings, which allow for longer flight times and continuous reconnaissance without the need for frequent refueling [52]. Similar is the case of the Skydweller project in the US Army [53]. In the navies, hydrogen fuel cell and biofuel-powered vessels, which can reduce the fleet's environmental footprint and increase self-sufficiency, are receiving increasing attention [54, 55]. All of these innovative solutions contribute to a more efficient and sustainable operation of NATO forces in the warfare of the future. In NATO's 2021 statement, the issue of solar technology was also raised in the case of tanks [56]. Tanks are extremely energy-intensive military equipment, the operation of which requires a significant amount of fuel [57]. The vast majority of the drive systems currently in use are based on internal combustion engines, which consume large amounts of fuel during their operation [58]. As a result, the logistical supply of tanks is a major challenge, especially during long-term operations [59]. In addition, conventional propulsion results in significant heat emission, which increases the vehicle's detectability, which is further heightened by the noise generated during engine operation [60, 61].

Hybrid drive systems, which combine conventional combustion engines with electric drives, are receiving more and more attention [62, 63]. These systems reduce fuel consumption, increase range, and reduce noise and heat emissions [64]. NATO member states are conducting a number of research projects to develop alternative energy supply systems that can be integrated into tanks and to increase operational efficiency through the use of complementary energy sources [65]. An example of such development is the new Abrams X tank (MBT), which has a hybrid electric propulsion, reducing fuel consumption by 50% while improving mobility and stealth capability [66]. In the infantry fighting vehicle (IFV) category, BAE Systems and Northrop Grumman have developed the Ground Combat Vehicle (GCV) hybrid electric powertrain (HED). It has fewer components, a smaller volume and it is lighter than conventional engines, while featuring high torque at start-up, smoother operation at low revs and even silent operation [67, 68]. In this context, Lee & Kim (2017) proposed a systematic methodology for hybrid military vehicle powertrains, integrating batteries and supercapacitors to optimize energy efficiency [69]. Randive et al. (2021) extended this line of research to tracked military vehicles, showing that hybrid powertrains with optimized transmission and storage

can cut fuel use by up to 30% while enhancing silent operation and tactical performance [70].

One of the latest developments in the MTU Series 199 engine family is a 10-cylinder hybrid engine version that delivers more than 1100 kW. This engine is ideal for heavy armored vehicles, and by using hybrid technology, the system reduces fuel consumption, enables the vehicle to operate quietly, and the vehicle's thermal image is drastically reduced in certain operating conditions [71]. One possible solution to deal with the above problems is to integrate PV technology into the power supply of tanks. The use of solar panels can not only result in a reduction in fuel consumption, but can also provide a tactical advantage [72], as it is possible to run the electrical systems continuously during periods of the day, even when the combustion engine is switched off, which can be particularly advantageous in hidden or waiting positions [73]. At the same time, Aghmadi & Mohammed (2024) reviewed high-power energy storage systems (Li-ion, supercapacitors, Superconducting Magnetic Energy Storage: SMES) and stressed their critical role in hybrid military power solutions, especially for supporting communication, UAVs, and electronic warfare subsystems [74].

By such developments, NATO aims to ensure the long-term competitiveness of the tanks currently in service, such as the Leopard 2, Abrams and Leclerc used by the Hungarian Defence Forces, while supporting the development of technological innovations for the next generation of tanks [75].

1.4 The Zrínyi 2026 program: Hungary's armored modernization efforts

An important goal of the Hungarian Defence Forces is the continuous development of national defense in order to provide modern and effective answers to the security challenges arising today. This is why the Hungarian Defence Forces launched the Zrínyi 2026 Modernization Program, which is one of the largest and most complex military technology modernization initiatives, which is not only aimed at strengthening national defense capabilities, but also aims to ensure Hungary's full cooperation with NATO [76]. This strategic initiative has become a priority due to the changing geopolitical and security environment and the challenges of modern warfare [77]. As a member of the European Union and NATO, it is essential for Hungary to have state-of-the-art military equipment in accordance with the obligations of the alliance and to be able to respond to the rapidly changing challenges of the global security situation [78]. The Zrínyi 2026 program includes, among other things, the procurement of new generation armored fighting vehicles [79].

Within the framework of the program, the Hungarian Defence Forces procured vehicles of the following types: the KF41 Lynx tracked infantry fighting vehicle, the Leopard 2A7 + HU tank and the PzH 2000 tracked self-propelled howitzer [80, 81]. The KF41 Lynx tracked infantry fighting vehicles manufactured by Rheinmetall are among the most modern armored fighting vehicles today and provide a high level of protection and firepower for rifle units. 209 units will be put into service [82]. In addition, the Hungarian Defence Forces have purchased 44 Leopard 2A7 + HU tanks, which will be used to modernize the domestic tank stock. In addition, 24 PzH 2000 tracked self-propelled howitzers have also been purchased, which ensures an increase in artillery firepower and allows for the quick and accurate destruction of distant targets [80, 81].

The energy supply systems of the equipment purchased within the framework of the program have been designed in accordance with modern military technology requirements. The engine of the KF41 Lynx tracked infantry fighting vehicle is a Liebherr D9612, a 6-cylinder internal combustion diesel engine that produces 1463 horsepower for the vehicle. This is the vehicle's only source of energy [83]. The Leopard 2A7 + HU tank is also equipped with an internal combustion engine, which is an MTU MB-873 Ka-501, a 12-cylinder internal combustion diesel engine with 1500 horsepower. However, unlike the KF41 Lynx, this vehicle is also equipped with an additional Auxiliary Power Unit (APU) system, which is able to provide the tank with an independent power supply even when the main engine is not working [84]. The APU system has been specifically integrated to improve fuel efficiency and ensure long-term operation, allowing the tank to be operated for longer periods of time without the main engine running continuously [85]. The PzH 2000 tracked self-propelled howitzers are also powered by an internal combustion engine, which is of the MTU 881 (8 cylinders and 1000 horsepower) type, and similarly the Hungarian Leopard 2, it is also equipped with an APU system [86].

1.5 The evolution of the Leopard 2 tank: technical development and combat readiness

The following description provides a concise overview of the development process of the Leopard 2 tank, with special regard to the Leopard 2A4 and Leopard 2A7 + HU variants in service in Hungary. The purpose of this is to provide a basis for the investigation to determine the extent to which PV technology can be applied in the energy systems of the tank and in the power supply of its individual elements. The aim of the research is not to present the history of development in full, but primarily to provide the background necessary for the examination of certain elements of the electrical systems. Thus, this chapter contributes to a deeper understanding of the tank, in terms of its electrical systems.

The development of the Leopard 2 tank was preceded by the MBT-70 (Kpz 70) tank program, run in U.S.-German cooperation [87]. This development project ultimately proved unsuccessful, mainly due to the high costs and disagreements due to the different military technical requirements of the participating countries. After that, Germany started the development of an MBT (main battle tank) on its own, which eventually resulted in the Leopard 2 [88]. The development of the Leopard 2 tank began in the early 1970s, in response to the Soviet tanks of the time (T-64, T-72) [89]. The goal was to create a main battle tank that would provide outstanding firepower, protection and mobility in accordance with the requirements of modern warfare. The development was led by the German company Krauss Maffei Wegmann (KMW) [90]. The first tanks were put into service in 1979 [91]. The main weapon of the tank was the smoothbore 120 mm L/44 cannon developed by Rheinmetall, which provided significant firepower [32]. Advances were also made in terms of armor: in contrast to the homogeneous steel armor of the Leopard 1 previously adopted by the German army (Bundeswehr), the Leopard 2A4, which was also adopted by Hungary, already used the British-developed "Chobham" layered armor [92].

The Leopard 2A4 version went into production in 1985 and included a number of improvements over the previous models. The most important of these was the new digital fire control system, which allowed for more accurate aiming and faster reaction times [93].

In the late 1980s, the German Army launched the *Kampfwertsteigerung* (KWS) program, which aimed to increase the combat value of the Leopard 2 tank. The program defined three main phases:

- KWS I: Development of the main armament: Rheinmetall developed the L/55 long-barreled 120 mm cannon, which provided a higher muzzle velocity and armor penetration. This development was implemented in the Leopard 2A6 version, the production of which began in 2001.
- KWS II: Improving protection and survivability: In the Leopard 2A5 model, a new tilted wedge-shaped turret was introduced, which provided better ballistic protection. At the turret, 'liners' were installed against the shrapnel effect. The fire control system was developed further. The driver's hatch was modified and the driver received a reversing camera. In 1995, conversions to this type version began in the German army. It is important to mention that, interestingly, it was the KWS II that was implemented first and only then the KWS I, because the German army considered the earlier introduction of the KWS II more important.
- KWS III: Its introduction was originally planned for 2008, and it involved the integration of a new turret, which would have had a 140 mm main armament, an automatic loading system and improved armor protection. Although the plans were completed, this phase was not implemented in the end, due to changes in the political environment and the end of the Cold War, when the military's development priorities were modified [65, 87].

The challenges of urban warfare called for the further development of the Leopard 2A6 tank [94]. As a result, the Leopard 2A7+ version was created, which is identical to the Leopard 2A7+HU type of the Hungarian Defence Forces, with minor differences [95]. The aim of the developments was to increase protection, reconnaissance capabilities and combat effectiveness. The tank's all-round reinforced armor provides increased protection against anti-tank missiles and improvised explosive devices [84]. A remote-controlled weapon rack was installed on the turret, which increased the effectiveness of the tank in urban combat against enemy forces [94]. To improve comfort and autonomy, air conditioning and a more powerful auxiliary engine were integrated too [96]. The advanced sensor systems include a driver night vision system that uses thermal imaging technology, and electro-optical systems that provide long-range day and night target detection. A new digital interface and command Battle Management System (BMS) improve data sharing and battlefield situational awareness [84]. To increase combat efficiency, a new programmable 120 mm ammunition was also introduced, providing a more flexible application and greater firepower against various targets [32, 93].

1.6 Research aim and scope: evaluating photovoltaic integration in leopard 2 systems

The aim of the present research is to investigate the extent to which PV technology can be applied in the energy systems of tanks or in the energy supply of their individual elements. The research focuses on the Leopard 2 type, as this tracked armored fighting vehicle is the most widely used in the NATO member states of the three previously mentioned types. The analysis explores the energy requirements of the electrical systems of the Leopard 2 and the characteristics of its operation.

Although there is growing interest in the use of renewable energy in military applications, especially within NATO frameworks, most existing studies focus on stationary infrastructure such as field bases, unmanned aerial systems, or hybrid military transport vehicles [97]. This is also reflected in Basar et al. (2025), who designed and simulated a hybrid hydrogen fuel cell military locomotive, demonstrating low-noise, low-emission operation for logistics and personnel deployment—underlining how renewable-based power can already be applied in heavy-duty military transport [98]. Likewise, Acanfora et al. (2021) demonstrated how additive manufacturing enables the development of hybrid metal/composite shock absorber panels for ejection seats, which significantly improve energy absorption with minimal weight increase. While not directly related to power generation, such innovations in lightweight and efficient design underline the broader trend of enhancing energy efficiency and survivability in modern defense technologies [99]. Research on renewable energy integration in heavy armored combat platforms, particularly main battle tanks, remains scarce [100]. To date, no comprehensive study has assessed the applicability of PV systems in supporting the electrical subsystems of the Leopard 2 tank. Moreover, while technologies such as hydrogen fuel cells, advanced batteries [97], and synthetic fuels [101] are being explored, photovoltaic systems offer unique advantages in certain tactical contexts. These include low acoustic signature, minimal mechanical complexity, rapid deployability, and the ability to provide power during daylight hours in stationary or passive operational states, without relying on the main engine [101]. This study therefore focuses deliberately on photovoltaic technology—not as a replacement for propulsion or full energy autonomy, but as a supplementary system aimed at powering select high-priority electrical subsystems. Special attention is given to active protection systems, which have become a critical requirement in modern warfare due to the widespread use of drones.

The research investigates whether PV-generated power, collected via a mobile solar trailer, can ensure operational readiness of these systems during hidden positioning, technical breakdowns, or non-movement scenarios. In doing so, the study contributes to the interdisciplinary discourse on energy resilience and technological adaptation in tactical defense platforms. Unlike hybrid-electric propulsion or hydrogen fuel cell systems—which often require significant structural modification, high-temperature tolerance, or complex logistical chains—photovoltaic energy systems are externally deployable, modular, and do not interfere with the internal architecture of the vehicle. Their use is therefore feasible even on legacy platforms without the need for major structural modifications or internal system redesign [102]. Furthermore, this research is not only in line with NATO's evolving military energy strategies but also connects to broader interdisciplinary themes. These include the ongoing global shift toward renewable energy, the logistics of defense operations, and the concept of resilience in high-demand energy systems. As such, the study offers a practical case for how sustainable energy technologies can support tactical autonomy and reduce dependency on traditional fuel supplies in mobile military platforms [103]. The main central question of the research is to what extent PV technology can complement or partially replace the traditional energy supply systems of the tank under such conditions.

To sum up the innovative significance of the present research, it can be stated that the application of PV technology in the power supply of tanks could represent not only technological development but also a new paradigm in the sustainability and tactical

application of military vehicles. The integration of alternative energy sources, such as solar energy, into the operation of tanks could provide an opportunity to introduce a new, environmentally friendly and efficient solution in addition to traditional fuel-based systems, which could reduce logistical burdens and environmental impacts. The continuous operation of electrical systems, the elimination of engine noise, and the possibility of covert operation can all provide tactical advantages that can significantly increase the survivability of tanks on modern battlefields. In addition, based on the experience of today's conflicts, it can be extremely useful to use an alternative energy supply system that is able to ensure the continuous power supply of the tank's active defense systems in the case of a stationary tank in order to protect against drones [104].

2 Materials and methods

2.1 Research method (overview)

The methodological framework of this research was designed to systematically assess the applicability of trailer-mounted PV systems for supplementing the electrical energy needs of a main battle tank. The process consisted of the following steps:

1. exploration of PV technologies: identification of possible stationary, mobile, and trailer-mounted PV solutions relevant to military field operations;
2. selection of system type (The study narrows its scope to trailer-mounted PV systems in order to evaluate their potential contribution to the auxiliary power supply of armored vehicles.);
3. geographical and irradiation analysis: mapping Hungarian training grounds and border areas, followed by the selection of representative sites to reflect both solar potential and defense relevance;
4. simulation of PV energy output: application of satellite-based irradiation datasets and a simulation platform to estimate the expected average energy production of the selected system type at representative Hungarian locations;
5. comparison with tank subsystems: relating the simulated average PV energy yield to the estimated energy demand of the Leopard 2A7 + HU's electrical subsystems, with emphasis on critical components during periods when the main engine is not operating.

This structured methodology ensures clarity and transparency, while providing a clear foundation for the detailed analyses presented in the subsequent sections.

2.2 Exploring the applicability of solar panels in the power supply of tanks

As the first step of the research, various solar power generation systems were examined, which could be used as possible energy sources for a tank waiting in an established position or standing in a camp. In this case, three main categories can be distinguished:

- Stationary solar panel systems: Stationary photovoltaic systems are solutions optimized for long-term, permanent applications, but can be relocated if necessary. These systems are often integrated into containers or installed on some kind of assemblable, disassemblable rack. All of them are characterized by the fact that they can be planted in camp conditions. Typical applications include operational bases, logistics centers, and humanitarian aid stations. The installed power can be up to several hundred kilowatts.

- Mobile solar systems: These are small, easy-to-transport devices that can be transported by light vehicles such as off-road vehicles or buggies. This construction can be carried on foot by either one person or a military squadron. These systems typically have a foldable or modular design so that they can be installed quickly and easily dismantled. Their power typically ranges from a few hundred watts to a few kilowatts, which is enough to power communication devices, computers, and other low-power military equipment. To increase energy efficiency, they are often combined with lithium-ion batteries.
- Mobile solar systems mounted on trailers: Higher-performance trailer-mounted photovoltaic systems offer significant advantages in terms of mobility and energy storage. These systems contain several square meters of solar modules and are often equipped with integrated energy storage systems (batteries) that allow for a continuous supply of energy even at night or in adverse weather conditions. These systems have an average power of 2–7 kilowatts, which allows them to supply power to communication centers and field hospitals. They can be quickly moved and installed thanks to their towability.

The research deliberately focused on evaluating the standalone performance of trailer-mounted PV systems without incorporating energy storage solutions, such as batteries. This methodological decision was grounded in both analytical clarity and the exploratory nature of the study. The primary aim was to establish a foundational understanding of how much continuous power can be generated directly from solar modules under realistic tactical conditions. By isolating the PV generation component, the analysis could provide a clear and undistorted view of the potential of solar energy as an immediate power source. While it is acknowledged that energy storage systems are integral to real-world military applications, their inclusion would have introduced significant variability and complexity into the model. Battery technologies differ not only in chemistry (e.g., lithium-ion, LFP, nickel-metal hydride) but also in terms of charge/discharge rates, weight, energy density, temperature tolerance, and lifecycle profiles. These parameters can drastically influence both tactical feasibility and energy supply continuity, making standardized modeling difficult without highly specific use-case data. Instead, the study adopts a boundary condition approach, treating the PV system as a standalone generator to map its maximum potential contribution during daylight hours. This forms a robust starting point for future research, which could build upon these findings by incorporating different types of energy storage technologies and military load scenarios. In this way, the current model acts as a controlled baseline—a ‘best case’ performance metric—against which more complex hybrid configurations (PV + battery) can be evaluated later. Thus, the omission of storage is not a disregard of operational realism but a strategic simplification that allows for the clear interpretation of solar generation capabilities alone. By doing so, the study remains internally consistent, methodologically transparent, and analytically scalable to future enhancements involving storage and load-specific modeling. At the same time, it should be noted that stand-alone PV generation represents a boundary condition rather than a realistic operational setting. In practice, photovoltaic systems are usually integrated into hybrid configurations that include batteries or auxiliary power units, which help to buffer the variability of solar energy and extend availability into night-time or low-irradiance conditions. Such solutions are central to real-world military applications, as they provide a more reliable and continuous supply

for critical subsystems. However, their inclusion in the present analysis would have introduced a level of complexity that risked obscuring the baseline performance of PV generation itself. The choice to focus on the stand-alone system was therefore a methodological simplification, ensuring transparency while still recognizing the significance of hybrid approaches. Accordingly, the results presented here should be understood as a starting point for more complex modeling rather than a comprehensive operational scenario. Hybrid systems remain outside the scope of this study, but their potential benefits are acknowledged and form a logical direction for subsequent work.

As a first step, the commercially available trailer solar systems which could be suitable for supporting the energy supply of tanks were mapped. Based on Table 1, they have different tilt angles and rated power, with the rated power ranging between 2400 and 7360 Wp, which is decisive for applicability. Based on the analysis of the market, the Solar Trailer HP46016G was selected. In addition to its nominal power of 7360 Wp, the decision was also justified by the fact that its design is robust, so it can also be moved in the field. The main technical characteristics of available trailer solar systems are shown in Table 1 [105–110].

2.3 Modelling considerations for the mobile solar panel system mounted on a trailer

2.3.1 Geographical points analyzed in the research

In the research, only locations within the territory of Hungary were analyzed. The primary reason for this restriction of geographical coverage is that the investigation focused on peacetime military exercises and the country's defense aspects. The test points were selected according to the following methodology:

- In the course of the research, all military training grounds in the territory of Hungary were collected on the basis of publicly available data (Fig. 1). As civilian sources do not provide complete and reliable information about which training grounds are suitable for the use of tracked armored fighting vehicles, the investigation relied solely on images available on the Internet and the official press releases of the Hungarian Defence Forces [111–124]. Based on the available sources, the vehicle types used in each training ground are listed in Table 2. Figure 1 visually illustrates the categorization of practice areas. The locations marked with red dots are those that are used for military exercises with tracked armored fighting vehicles.
- In order to take into account border protection aspects, seven more geographical points were identified at the borders of Hungary (marked with a green dot in Fig. 2), which play a key role in international border traffic [125, 126]. Each of these points is linked to border crossings with key neighboring countries. The reason for the selection is that in the event of a threat from the direction of any neighboring country, these crossing points can play a key role in border protection, so their protection significance is extremely high.

In the analysis, a map representing Hungary's Global Horizontal Irradiation (GHI) (see Fig. 2) was used [127]. Based on the map, the territory of Hungary can be divided into different irradiation zones showing different values of global radiation. In order to ensure that the different irradiation zones are represented, and considering the fact that several geographical points (training grounds/border crossing points, see Fig. 1) also fall into the same irradiation zone, the number of examined geographical points was optimized.

Table 1 Solar trailers suitable for supplying power to tanks (*estimate) (own editing)

Manufacturer	Product name	Tilt angle (°)	Peak power (Wp)
RPS solar pumps	Sun Titan™	30*	2760
OkSolar	Solar Trailer Item no.: 000777000	35*	2400
BIGLUX	Solar Trailer Model no.: HP46016G	35*	7360
BigBattery	Solar Trailer Nr.: K0727	0–90	2400
ECOSUN	TRAILER-WATT® 15S	15	5600
UnivPower	S4800G-0004	30*	7280

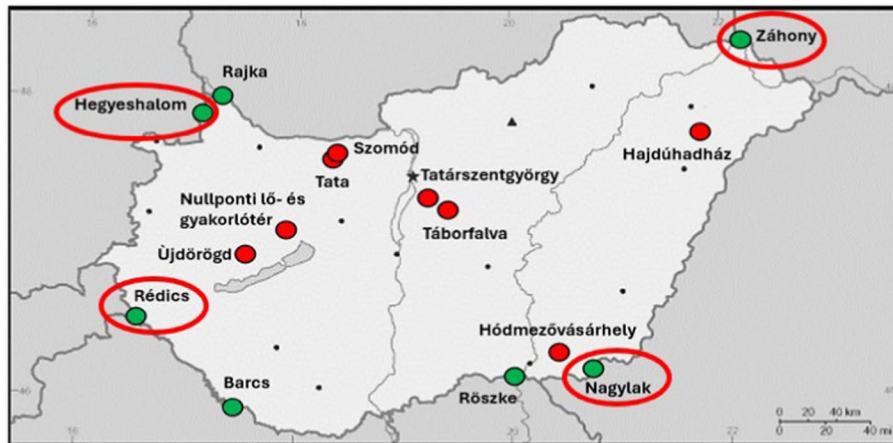


Fig. 1 The locations of training grounds in Hungary (red dots) and the most important border crossing points (green dots) (own editing based on [125, 126])

Table 2 The tracked armored fighting vehicles used on each training ground based on available sources (own editing)

Training grounds in Hungary	
Name of the training ground	Tracked armored fighting vehicles used on the training ground, based on available sources
Hajdúhadház	T-72
Hódmezővásárhely	KF41 Lynx
Nullponti lö- és gyakorlótér	T-72, KF41 Lynx, Leopard 2, PzH 2000
Szomód	T-72, Leopard 2, PzH 2000
Tata	T-72, Leopard 2, PzH 2000
Tatárszentgyörgy	KF41 Lynx
Táborfalva	KF41 Lynx
Újdörög	KF41 Lynx

Thus, based on the comparison of Figs. 1 and 2, four geographical points were selected for a more detailed examination, which are marked separately in Fig. 1:

- Hegyeshalom (47.9023° N, 17.1418° E);
- Nagylak, (46.1694° N, 20.6097° E);
- Rődics (46.6158° N, 16.4683° E);
- Záhony (48.4089° N, 22.1758° E).

These settlements are located in different regions of the country and represent the different irradiation zones well, allowing for a more accurate analysis of regional variations in irradiation conditions. In addition to covering Hungary’s key solar irradiation zones,

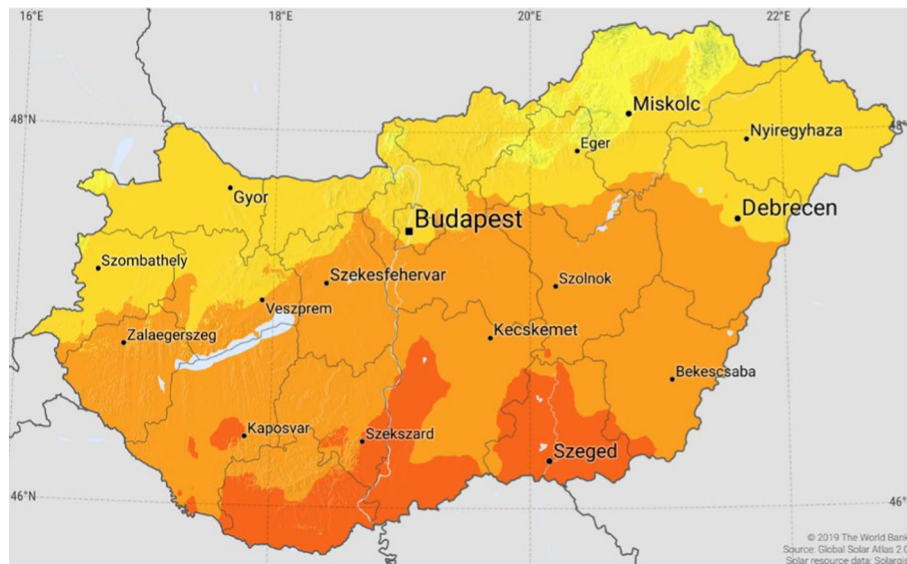


Fig. 2 The global horizontal irradiation map of Hungary (GHI) [127]

the selected four locations were chosen for their combined operational and strategic significance. Each site either hosts or is closely associated with tracked armored vehicle activity or serves a critical role in border security—or both. For example, Hegyeshalom, Rédics, and Nagylak are situated near border crossings while being linked to training grounds where Leopard 2, KF41 Lynx, and PzH 2000 vehicles are active (see Table 2, Fig. 1). Although Záhony lacks an adjacent tank training site, its status as one of Hungary's most important logistics gateways underscores its defense relevance. This dual rationale—combining solar suitability with military deployment realism—ensures that our PV system assessment reflects authentic tactical and geographic scenarios.

2.3.2 Global solar atlas database

In the course of the research, the Global Solar Atlas online database was used to investigate the potential of trailer-mounted mobile solar systems to provide the Leopard 2 tank with power supply.

The Global Solar Atlas is a publicly available, interactive map-based application developed by the World Bank and the Energy Sector Management Assistance Program (ESMAP) with the aim of providing reliable and detailed solar potential data worldwide. The system collects data from a variety of sources, including satellite observations, data from terrestrial weather stations, and numerical weather models. The collected data is processed using computational models and simulations that take into account climate specificities. In the Global Solar Atlas (GSA) system, different parameters are available for a given area, such as global horizontal irradiation (GHI), direct normal irradiation (DNI) and diffuse horizontal irradiation (DIF). The system also provides long-term meteorological data, which helps to predict solar energy utilization potential in a more specific way. The data can be downloaded in various formats, such as CSV and GIS files, so users can use it extensively [128–130].

The GSA can be widely used, especially in PV-based energy generation planning. It provides reliable data for investors, researchers and developers, helping to reduce financial risks, and helps universities and research institutes with analyzing climate models

and renewable energy sources. The app is an easy-to-use, browser-based system that does not require any software installation.

To estimate the energy output of the mobile PV system mounted on the BIGLUX HP46016G military-grade trailer, the Global Solar Atlas (GSA) platform was used. The system's total installed capacity of 7.36 kWp, a south-facing azimuth of 180°, and a fixed tilt angle of 35°—all reflecting the actual mechanical configuration of the trailer—were entered directly into the GSA interface to ensure that simulation results closely reflect real-world operating conditions. The GSA, developed by the World Bank Group and Solargis, uses satellite-based solar resource and meteorological data combined with PV performance modeling algorithms to generate reliable photovoltaic output profiles. The “average hourly profiles” module was used to calculate hourly energy production values in watt-hours (Wh) for each day of the year. The simulation covered the four selected, geographically distinct Hungarian locations—Hegyeshalom, Nagylak, Rédics, and Záhony—to evaluate spatial differences in energy yield. The outputs represent the expected net energy generation of a 7.36 kWp system under local irradiation and meteorological conditions. The exported hourly datasets were compiled into monthly tables (Tables 3, 4, 5, 6), providing average hourly energy yield across a full 24-h period. This dataset formed the primary basis for evaluating the feasibility of supplying various subsystems of the Leopard 2A7 + HU tank, including mission-critical components such as the communication equipment and the active protection system, using the trailer-mounted PV solution. This simulation-based approach ensured methodological transparency and realism, as it directly integrates real-world technical parameters. It reinforces the reliability and relevance of the study's findings concerning the military applicability of photovoltaic systems in field operations, especially in relation to their potential to supplement or partially sustain the energy demands of armored military assets under optimal conditions.

Tables 3, 4, 5, 6 illustrate the average daily energy yield at the examined geographical locations (Hegyeshalom, Nagylak, Rédics, Záhony) on a monthly basis, taking into account the entire 24-h time period. Mapping these is of great importance because it can be used to determine the periods in which enough PV energy is available to supply the individual electrical systems of the Leopard 2 tank. Energy quantities are expressed in watt-hours (Wh). Based on the comparison of the PV-based energy production at the four places (Hegyeshalom, Nagylak, Rédics and Záhony), only minor differences could be observed between their respective values of the different months and times of day in the case of the examined trailer PV system. In all four locations, the highest energy production can be achieved during the summer months (June to August) due to the increased hours of sunshine and the more favorable angle of the sun's height. The lowest values can be observed in the winter months (December, January), which can be explained by shorter days and lower irradiation angles. Nagylak shows the highest aggregate annual energy production for the PV technology under review, which is 300.2 kWh, while in the case of Záhony it is 286.7 kWh, which is the lowest annual energy production value among the examined locations.

The hourly resolution energy data of the four settlements show a similar pattern during the day. The PV system's energy production typically starts around 6–7 a.m. and reaches its maximum around noon. The highest energy yield occurs between 10 a.m.

Table 3 The average daily energy yield in Hegyeshalom in the case of the PV system examined (own editing)

Time of day / Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0–1 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
1–2 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
2–3 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
3–4 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
4–5 (Wh)	0	0	0	0	18	52	19	0	0	0	0	0
5–6 (Wh)	0	0	0	66	257	332	256	107	9	0	0	0
6–7 (Wh)	0	0	124	599	887	944	821	662	411	71	0	0
7–8 (Wh)	3	240	952	1616	1834	1889	1753	1634	1324	893	239	15
8–9 (Wh)	661	1273	2025	2666	2772	2823	2734	2660	2306	1772	1054	592
9–10 (Wh)	1411	2091	2865	3506	3538	3563	3533	3497	3124	2439	1643	1210
10–11 (Wh)	1742	2601	3321	4008	4000	4075	4000	3998	3581	2808	1934	1529
11–12 (Wh)	1978	2928	3615	4230	4124	4217	4156	4181	3776	3054	2147	1731
12–13 (Wh)	2065	3019	3631	4145	4073	4091	4081	4151	3685	3069	2087	1726
13–14 (Wh)	1823	2836	3401	3737	3733	3729	3726	3744	3238	2637	1769	1465
14–15 (Wh)	1312	2183	2711	3069	3097	3120	3124	3107	2599	1958	1202	993
15–16 (Wh)	493	1412	1906	2213	2342	2419	2455	2310	1751	1102	362	247
16–17 (Wh)	4	349	980	1294	1460	1590	1606	1436	873	146	0	0
17–18 (Wh)	0	0	108	407	592	738	759	549	92	0	0	0
18–19 (Wh)	0	0	0	13	138	254	233	53	0	0	0	0
19–20 (Wh)	0	0	0	0	0	21	11	0	0	0	0	0
20–21 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
21–22 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
22–23 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
23–24 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
Sum (kWh)	11.5	18.9	25.6	31.6	32.9	33.9	33.3	32.1	26.8	19.9	12.4	9.5

and 2 p.m., then gradually decreases in the afternoon. After 6 p.m., energy production is negligible.

The differences between the locations are due to climatic and geographical differences. Such is the number of sunshine hours, which, due to its southernmost location, is the highest in Nagylak, receiving slightly more hours of sunshine during the year than Záhony [131]. As for the weather factors, a wetter and more humid climate reduces energy production. Due to its northern location, Záhony is more often exposed to cloudy weather [132]. The biggest differences in energy yield can be seen in the winter months, when the differences between the examined locations are more noticeable.

Based on the annual distribution of energy production, it can be said that the examined trailer-mounted PV system would work best in the spring and summer months, while energy production drops significantly in the winter months. Based on the analysis in Tables 3, 4, 5, 6, it can be seen that the PV energy production in the four settlements follows similar patterns with small differences. It can be observed that there are only minimal regional differences in the average PV energy production in Hungary, so the national distribution can be considered almost homogeneous.

2.4 The Leopard 2 main battle tank

The focus of the research was on the examination of the electrical systems of the Leopard 2 main battle tank, with special regard to its energy requirements and the feasibility of its partial photovoltaic electricity supply. Since it is a military device, many of its technical characteristics are strictly classified, and the exact manufacturer's data are not always available.

In the absence of available data, the values were determined by estimation or, where this was not possible, the respective elements were not considered in the analysis. The study focused primarily on the larger functional units and their energy consumption, thus avoiding the fragmentation of research due to excessive detail. In addition, the present research provides a comprehensive but concise theoretical overview without engaging in detailed technical analysis. The following electrical systems were examined:

- navigation and positioning system elements;
- reconnaissance and sighting system elements;
- communication system elements;
- weapon system and secondary armament;
- protection;
- additional supporting electrical systems.

One of the goals of the research was to explore and compare the energy requirements of different electrical systems of the tank. Based on this, it was determined how long the daily average energy yield of the mobile solar panel system mounted on the BIGLUX Solar Trailer HP46016G PV trailer can provide sufficient energy for each system during sunny periods, at the previously defined geographical points.

As an innovative aspect of the present study, the system components whose autonomous operation (i.e. continuous supply of electricity) is of critical importance in the event of damage to the tank, have been identified on the basis of experience gained in today's most significant conflicts involving the use of tanks (Ukraine, Gaza). Within the framework of the investigation, the required amount of energy and the possibility of

Table 4 The average daily energy yield in Nagylak in the case of the PV system examined (own editing)

Time of day / Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0–1 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
1–2 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
2–3 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
3–4 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
4–5 (Wh)	0	0	0	0	32	94	45	0	0	0	0	0
5–6 (Wh)	0	0	4	121	343	400	339	174	31	0	0	0
6–7 (Wh)	0	0	278	757	1086	1130	1050	909	636	286	0	0
7–8 (Wh)	116	477	1267	1767	2088	2148	2077	1999	1661	1330	500	113
8–9 (Wh)	980	1520	2327	2794	3043	3154	3080	3094	2686	2297	1470	921
9–10 (Wh)	1637	2273	3186	3602	3764	3843	3858	3926	3454	3019	2124	1489
10–11 (Wh)	1963	2738	3705	4043	4136	4220	4288	4363	3851	3398	2431	1725
11–12 (Wh)	2131	2941	3882	4100	4198	4232	4328	4463	3937	3553	2598	1817
12–13 (Wh)	2111	2940	3751	3939	4001	4053	4177	4260	3702	3397	2435	1737
13–14 (Wh)	1834	2670	3333	3487	3547	3609	3792	3812	3148	2771	1957	1410
14–15 (Wh)	1248	1987	2557	2722	2838	2976	3131	3121	2428	1945	1254	860
15–16 (Wh)	406	1149	1691	1908	2065	2226	2351	2214	1590	985	332	92
16–17 (Wh)	0	155	768	1012	1179	1351	1428	1249	664	87	0	0
17–18 (Wh)	0	0	50	225	422	545	577	350	28	0	0	0
18–19 (Wh)	0	0	0	0	47	151	129	7	0	0	0	0
19–20 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
20–21 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
21–22 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
22–23 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
23–24 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
Sum (kWh)	12.4	18.9	26.8	30.5	32.8	34.1	34.7	33.9	27.8	23.1	15.1	10.2

providing it by using the examined mobile PV system were determined. To address the real-world applicability of the PV system, the study integrates considerations of Leopard 2 operational behavior into its methodological framework.

Given the operational complexity of modern armored warfare, Leopard 2 tanks are not in constant motion but frequently alternate between active maneuvers and strategically planned passive deployments. These passive phases—such as concealed positioning, long-duration idle states, or defensive hold positions—are increasingly emphasized in current doctrines, particularly in environments where drone surveillance and precision strikes pose a high risk. In such scenarios, tank crews often switch off the main engine to reduce acoustic and thermal signatures, which significantly lowers detectability. However, the PV trailer itself could present a detectable signature—both thermally and visually—if placed directly adjacent to the tank. Therefore, tactical deployment may require spatial decoupling, with the trailer positioned at a concealed distance and connected via cabling to minimize exposure. Despite engine shutdown, critical subsystems must remain continuously powered. These include active protection systems (APS), communications equipment, thermal imaging, and surveillance sensors—all of which are essential for situational awareness and survival under drone-contested conditions.

This study explicitly aligns its methodology with the above-mentioned passive operational patterns. Rather than simulating full mission autonomy or propulsion-level energy replacement, the research focuses on a realistic tactical window where PV systems—specifically trailer-mounted solar arrays—could provide sustained auxiliary power to support electronic subsystems during engine-off states. These windows are not marginal exceptions but integral parts of modern tank usage in conflicts such as Ukraine and Gaza, where prolonged stationary deployments are tactically necessary. By analyzing whether the PV trailer can meet the power demands of critical subsystems during such idle phases, the study offers a practically grounded assessment of solar viability in armored platforms. This approach ensures that the findings are not merely technical but also tactically meaningful, as they reflect real-world military deployment patterns rather than idealized or constant-activity scenarios.

2.4.1 The most important electrical system component

From the point of view of the research, it was important to determine which system elements are of paramount importance based on the analysis of contemporary conflicts. At the time of the research, the two most significant armed conflicts involving the use of tanks are taking place in the Gaza Strip and Ukraine. The choice of these two conflicts as reference is justified by the fact that their analysis contributes to emphasizing the topicality of the study, and they provide the most recent empirical data on the use of tanks in the theater of war.

Many articles and studies have dealt with the phenomenon that the role of drones on the battlefield has increased significantly in modern warfare in the two above-mentioned conflicts [133–135]. Several sources have analyzed that these low-cost devices pose a serious threat to significantly more expensive tanks, thus raising the question of whether tanks are still appropriate tools for present-day military deployment [136–138]. The role of tanks is changing due to the rapid development of drone technology, as drones are playing a key role in both reconnaissance and precision strikes, having a significant impact on armored warfare [139, 140].

Table 5 The average daily energy yield in Rédics in the case of the PV system examined (own editing)

Time of day / Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0–1 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
1–2 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
2–3 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
3–4 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
4–5 (Wh)	0	0	0	0	14	40	11	0	0	0	0	0
5–6 (Wh)	0	0	0	42	236	303	224	83	7	0	0	0
6–7 (Wh)	0	0	88	538	818	885	760	613	372	69	0	0
7–8 (Wh)	10	262	923	1503	1781	1817	1680	1596	1255	869	200	17
8–9 (Wh)	773	1362	1985	2526	2738	2768	2691	2613	2236	1785	1095	693
9–10 (Wh)	1587	2237	2904	3332	3534	3579	3515	3494	3082	2498	1726	1356
10–11 (Wh)	2016	2789	3465	3830	3978	4074	4063	4069	3596	2983	2036	1703
11–12 (Wh)	2257	3155	3762	4050	4119	4232	4240	4306	3806	3273	2285	1940
12–13 (Wh)	2350	3249	3749	3996	4023	4172	4220	4260	3721	3300	2276	1954
13–14 (Wh)	2155	3074	3529	3605	3688	3819	3908	3921	3334	2872	1968	1704
14–15 (Wh)	1638	2431	2839	2983	3086	3216	3315	3288	2667	2162	1361	1195
15–16 (Wh)	690	1610	2030	2173	2363	2490	2587	2446	1861	1242	482	375
16–17 (Wh)	4	535	1095	1283	1483	1611	1700	1507	937	184	0	0
17–18 (Wh)	0	0	135	427	616	753	775	564	106	0	0	0
18–19 (Wh)	0	0	0	20	126	238	232	34	0	0	0	0
19–20 (Wh)	0	0	0	0	0	7	10	0	0	0	0	0
20–21 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
21–22 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
22–23 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
23–24 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
Sum (kWh)	13.5	20.7	26.5	30.3	32.6	34.0	33.9	32.8	27.0	21.2	13.4	10.9

Table 6 The average daily energy yield in Záhony in the case of the PV system examined (own editing)

Time of day / Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0–1 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
1–2 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
2–3 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
3–4 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
4–5 (Wh)	0	0	0	0	73	127	74	4	0	0	0	0
5–6 (Wh)	0	0	4	160	413	475	384	232	47	0	0	0
6–7 (Wh)	0	0	314	860	1194	1245	1107	984	684	277	0	0
7–8 (Wh)	74	459	1316	1886	2202	2228	2089	2056	1680	1213	451	54
8–9 (Wh)	846	1380	2356	2904	3119	3150	3020	3086	2608	2068	1221	701
9–10 (Wh)	1462	2075	3204	3664	3821	3862	3734	3843	3340	2698	1740	1183
10–11 (Wh)	1687	2441	3635	4030	4170	4216	4177	4281	3713	2979	1942	1350
11–12 (Wh)	1800	2626	3800	4095	4227	4257	4230	4420	3786	3143	2023	1446
12–13 (Wh)	1764	2608	3675	3956	4083	4066	4097	4269	3604	2976	1966	1376
13–14 (Wh)	1536	2388	3299	3509	3614	3672	3689	3809	3072	2436	1568	1101
14–15 (Wh)	1023	1750	2510	2767	2888	3003	3022	3069	2354	1686	875	595
15–16 (Wh)	158	956	1618	1889	2075	2202	2191	2116	1498	693	84	32
16–17 (Wh)	0	96	608	959	1173	1326	1321	1163	549	41	0	0
17–18 (Wh)	0	0	24	199	405	526	532	310	25	0	0	0
18–19 (Wh)	0	0	0	0	47	161	126	7	0	0	0	0
19–20 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
20–21 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
21–22 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
22–23 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
23–24 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
Sum (kWh)	10.4	16.8	26.4	30.9	33.5	34.5	33.8	33.6	27.0	20.2	11.9	7.8

The widespread use of drones in Ukraine has made it possible to constantly monitor enemy tanks, as well as attack them using inexpensive, even home-modified devices [141]. Precision-guided First Person View (FPV) drones and Unmanned Aerial Vehicles (UAVs) have significantly increased tank losses, forcing the introduction of new tactics and technological advancements [142, 143].

A similar trend can be observed in the Gaza conflict, where the Gazan side, which is engaged in asymmetric warfare, uses drones against Israeli units [144].

Based on the experience of conflicts, the future use of tanks requires the integration of new protection systems (e.g. active protection, anti-drone devices). The interaction between tanks and drones does not, therefore, mark the end of armored warfare, but a new era in which conventional armored forces are increasingly complemented and protected by modern electronics and drone protection solutions. This insight is essential for the results of this research.

3 Results

3.1 The electrical systems of the Leopard 2 main battle tank

Table 2 shows the energy requirements of the electrical systems of the Leopard 2A7 + HU tank. This variant was chosen because it is the version that is used in the largest number by the Hungarian Defence Forces and the research focuses on Hungary. As it is a military device, many of its technical data are classified, and the manufacturer's specifications are not available for certain system components. Therefore, estimated values were considered in several cases. The study covered only the main electrical systems, grouped according to functional aspects, as a detailed analysis of all electrical components would have led to an excessive fragmentation of the research.

Based on the results in Table 7, it can be seen that the various on-board electrical systems of the Leopard 2A7 + HU tank operate with significant energy consumption, which is provided by the main engine and an auxiliary power source (APU).

The tank's electrical supply is basically provided by a generator on the main engine manufactured by MTU/Rolls-Royce Solutions, which is capable of delivering 20 kW of power. This is complemented by the Steyr M12 APU, which also provides 20 kW of power for the on-board systems. The role of the APU is paramount, as it allows the vehicle to operate its basic systems without the main engine running, thus reducing fuel consumption.

The tank's GPS and inertial positioning system, supplied by LITEF, operates with extremely low energy requirements with a power consumption of only 0.012 kW.

There is no official source or measurement data available for the energy requirement of the Battle Management System (BMS). Moreover, there is no available data on the energy consumption of any systems similar in their technical parameters, so it was not possible to determine its accurate/estimated power demand.

The components of the reconnaissance and sighting system of the tank represent low energy needs. The EMES 15 main sight manufactured by Atlas Elektronik GmbH/Rheinmetall, which is the tank's primary fire control system, has an unknown energy requirement. By contrast, the energy consumption of the additional sight systems supplied by Hensoldt is as follows:

- FERO Z18 gunner auxiliary sight: 0.03 kW;
- PERI R17A3 commander sight: 0.02 kW;

- HENSOLDT SPECTUS II driver's sight system: 0.07 kW.

Together, these sight systems represent a relatively low energy requirement, with a total power consumption of about 0.12 kW.

The E-LynX radio system of the tank has an energy requirement of about 0.03 kW. As no precise specifications were available, this value was estimated as follows. The E-LynX military radio has a total output power of 100W, which is divided into two channels with 50W of power each. The device works with a 24 V power supply. Since the transmitters do not have 100% efficiency, various losses occur during their operation. As a result, the actual power consumption of the system exceeds the rated output power. For a typical military radio transmitter, the total electrical consumption is typically 2 to 3 times the output power, considering the power requirements of the power stages, cooling system, and digital circuits. Based on this estimate, the minimum estimated power consumption of the radio is approximately 200 W, while the maximum power consumption can reach 300 W.

No data were available on the power demand of the SOTAS-IP intercom system, but based on other similar systems, it can be assumed to be in the order of a few hundred watts [145].

Table 7 The main electrical systems of the Leopard 2A7 + HU (own editing)

The electrical systems of the Leopard 2A7 + HU				
Electrical system elements	System name	Manufacturer	Power demand (kW)	Source
Generator (driven by main engine)	–	MTU / Rolls-Royce Solutions GmbH	20	[85]
APU (Auxiliary power unit)	Steyr M12 2-cylinder diesel APU	Steyer	20	[128]
<i>Navigation and combat control system elements</i>				
GPS and inertial positioning	LLN-GY	LITEF	0.012	[153]
BMS (Battle management system)	INIOCHOS	Rheinmetall	???	[154]
<i>Reconnaissance and sighting system elements</i>				
Gunner main sight	EMES 15A2	Atlas Elektronik GmbH / Rheinmetall	???	[84]
Gunner auxiliary sight	FERO Z18	Hensoldt	0.03	[155]
Commander sight	PERI R17A3	Hensoldt	0.2	[156]
Driver's sight system	HENSOLDT SPECTUS II	Hensoldt	0.07	[157]
<i>Communication system elements</i>				
Radio	E-LynX	ELBIT SYSTEMS	0.03*	[158, 159]
Intercom	SOTAS-IP	Thalesgroup	???	[148]
<i>Weapon system and secondary armament</i>				
Stabilizer	GTD chaserV system	VINCORION	23*	[147]
RCW	FLW 200	KNDS	1	[160–163]
<i>Protection (this system is not available in the Hungarian Leopard 2A7 + HU, only in versions A7A1 and A8)</i>				
Active protection	TROPHY	Rafael / Leonardo DRS	3750	[164]
<i>Additional auxiliary electrical systems</i>				
Air conditioning and NBC system	–	–	8	[165]

Values marked with an asterisk (*) are estimated based on literature sources

The energy requirements of the weapon system and secondary armament are among the most significant electrical loads of the tank. The GTD ChaserV stabilizer system has an energy requirement of about 20 kW, which is in line with the data of stabilizers of similar performance [146]. On the basis of the manufacturer's data the following estimates were made for the purposes of the present study [147, 148]:

- Stabilizer power supply: 18 V DC–32 V DC and 600 V DC–800 V DC.
- The maximum torque for elevation (vertical motion in this case) is 32,000 N (linear force) with a stroke of 205 mm. Maximum speeds for azimuth movement $\geq 40^\circ/s$.
- The torque of azimuth motion (horizontal motion) is 1 100 Nm at a maximum speed of 115 rpm. Maximum speeds for elevation $\geq 40^\circ/s$.
- Thus, the estimated maximum power demand of the azimuth drive can be determined by the following (Eq. 1) equation [149]:

$$P = M \times \omega = \frac{1100 \times 115 \times 2 \times \pi}{60} = 13.25 kW \quad (1)$$

where P (kW) is the power for rotational motion, M (Nm) is the torque, and ω (1/min) is the angular velocity.

The estimated maximum power requirement of the elevation drive (Eq. 2) [149]:

$$v = \frac{s}{t} = \frac{0.205}{t \text{ (no catalogue data)}} = 0.205 m/s \quad (2)$$

In the formula, v (m/s) is the velocity, s (m) is the distance, which in this case is the stroke. And t is the time (s).

The time t (s) was estimated as follows: The maximum gun elevation angle range of the Leopard 2 is $-9^\circ/+20^\circ$ (total range: 29°) [150]. Knowing the maximum velocity for elevation $\geq 40^\circ/s$, the time can be determined as follows:

Calculating the time (Eq. 3):

$$v = \frac{\text{whole range}}{t} \Rightarrow t = \frac{\text{whole range}}{v} = \frac{29}{40} = 0.725 \text{ s} \quad (3)$$

Thus, the estimated maximum power requirement of the elevation drive (Eq. 4):

$$v = \frac{s}{t} = \frac{0.205}{0.725} = 0.283 m/s \quad (4)$$

With the next step (Eq. 5), the elevation power requirement was calculated by the following calculation [149]:

$$P = F \times v = 32000 \times 0.283 = 9.06 kW \quad (5)$$

In the formula, P (kW) is the power, F (N) is the force requirement for vertical displacement. And v (m/s) is the speed of displacement.

This is how the estimated total power requirement of the stabilizer system is given (Eq. 6)

$$P_{total} = P_{azimuth} + P_{elevation} = 13.25 + 9.06 = 22.31 kW \quad (6)$$

where P_{total} (kW) is the total energy requirement of the stabilizer, $P_{azimuth}$ (kW) is the energy requirement for horizontal motion and $P_{elevation}$ (kW) is the energy requirement of vertical movement.

The FLW 200 Remote Controlled Weapon Station (RCWS) by KNDS has an estimated power requirement of 1 kW. The power requirement of the Remote Controlled Weapon Station was estimated based on the data of two remote-controlled weapon stations with similar weight and armament [151, 152]. In the case of the systems examined, the power required for operation was approximately 1 kW, so this value was used as the basis for the calculations.

The Leopard 2A7+HU tank does not currently have an active defense system, but there are already Leopard 2 versions with such a system integrated, which presumably creates an opportunity to supplement the Hungarian version in the future. As established in the methodological section in the examination of the most important electrical system elements, active defense systems will become one of the decisive technological elements of the future in increasing the defense capabilities of modern tanks. In light of this, the examination of these systems is of paramount importance considering the potential modernization of the domestic Leopard 2 fleet or the acquisition of newer versions already equipped with an active protection system. This is also supported by the fact that more advanced versions of the Leopard 2, such as the Leopard 2A7A1 and Leopard 2A8 models, use the TROPHY active protection system, which has an energy requirement of 3.75 kW.

The auxiliary systems, such as the air conditioning and the NBC system, have an energy consumption of 8 kW each, which is a significant factor, especially in extreme temperatures.

As mentioned above, the Leopard 2 tank is powered by both the main engine and the Auxiliary Power Unit (APU), both capable of providing 20 kW of electrical power. It is important to note that the APU will automatically stop operating when the main engine is running or when the openings that must be closed to overcome deep fords are closed [85]. The theoretical maximum energy requirement of the various electrical systems of the tank is about 30 kW. However, this value does not mean that all systems operate simultaneously and at maximum load, as the load of the systems varies during practical operation and they typically do not reach their maximum consumption at the same time. To bridge momentary peak loads, the batteries of the tank can be used, which can provide additional energy for a short time. Based on the available data, it can be concluded that 20 kW of power is sufficient for the continuous power supply of the electrical systems of the Leopard 2 tank, which can be provided by the main engine generator or the APU. Since neither original factory data nor on-site measurements in different operating modes were available, the findings are based solely on theoretical conclusions.

Based on the daily average PV energy production data of the geographical locations described in the methodological section (Tables 3, 4, 5, 6), where the maximum value was 4.4 kWh, it can be clearly stated that the BIGLUX Solar Trailer HP46016G PV trailer is not able to provide the amount of energy required for the operation of the tank's electrical systems. Therefore, the system mounted on the solar trailer in question cannot be considered a realistic alternative solution of this magnitude. However, it is an important question which tank systems can be partially supported by the PV system, and to what extent it can reduce dependence on external energy sources.

3.2 PV-based power supply for the active defense of the Leopard 2 tank

Having established that the full PV-based electrical energy supply of a tank is not feasible, the next step was to examine which electrical systems of paramount importance can receive a sufficient amount of energy for their operation from the solar trailer. To determine this, the background information was provided by the conflicts currently taking place with the participation of tanks, described in the methodology chapter. Based on the experience of current armed conflicts, protection against drones has become one of the most critical capabilities for tanks. Accordingly, the possibility of operating the components of the active protection system with the help of the PV power supply under investigation was examined. If this is feasible, the protection of a tank could be ensured not only in the case of storage in the barracks, but also in the case of waiting in a hidden position or in the event of a possible breakdown.

Upon customers' request, KNDS, the manufacturer of the Leopard 2 tank, officially equips the Leopard 2 with the Israeli-developed Trophy active protection system [165], which has also been adapted to protect against drones [166]. In light of this, the next step of the research was to determine the electrical energy demand of the Trophy active protection system. Subsequently, this value was compared with the technical parameters of the trailer selected for analysis, and then the amount of electrical energy that could be produced and its sufficiency for the operation of the system were evaluated for the previously defined geographical locations.

According to the manufacturer's catalogue, the maximum energy requirement of the Trophy active protection system [164] is 3.75 kW.

Considering the geographical points defined in the methodology chapter, depending on the energy demand of the active protection system, the following purely PV-based operating periods have been determined in the case of using a BIGLUX Solar Trailer HP46016G PV trailer. In Tables 8, 9, 10, 11, only those periods are indicated and highlighted in yellow for which the solar trailer is able to provide the active protection system with a continuous energy supply. In addition, the table shows in aggregate the percentage of the average daily energy production of a given calendar month that is actually suitable (green cells) for the energy supply of the active protection system.

3.2.1 PV power generation periods

The length and intensity of PV power generation periods are a determining factor in the efficiency of PV-based energy supply. The number of hours of sunshine, geographic location, and seasons all affect power.

- Hegyeshalom: The PV energy required for the continuous operation of the active protection system is only available during daylight hours, mostly from 10:00 to 13:00. The highest production potential can be observed from April to June, when the hourly energy production exceeds 4200 Wh. Due to the limited number of hours of sunshine during the winter months, PV production does not provide enough energy for the system to run continuously.
- Nagylak: The operation of the active protection system is possible between 9:00 and 14:00, which ensures a longer period of time than in the case of Hegyeshalom. The highest production potential can be observed in the months of July and August, when the hourly energy production exceeds 4300 Wh. From October, due to decreasing solar radiation, PV production no longer provides enough energy for

Table 8 The potential periods of purely photovoltaic energy supply in Hegyeshalom (own editing)

Time of day / Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0–1 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
1–2 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
2–3 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
3–4 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
4–5 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
5–6 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
6–7 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
7–8 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
8–9 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
9–10 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
10–11 (Wh)	0	0	0	4008	4000	4075	4000	3998	0	0	0	0
11–12 (Wh)	0	0	0	4230	4124	4217	4156	4181	3776	0	0	0
12–13 (Wh)	0	0	0	4145	4073	4091	4081	4151	0	0	0	0
13–14 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
14–15 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
15–16 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
16–17 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
17–18 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
18–19 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
19–20 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
20–21 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
21–22 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
22–23 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
23–24 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
Sum (kWh)	0.00	0.00	0.00	12.38	12.20	12.38	12.24	12.33	3.78	0.00	0.00	0.00
Proportion of utilizable energy (%)	0%	0%	0%	39%	37%	37%	37%	38%	14%	0%	0%	0%

the continuous operation of the active protection system, so its application is not possible during this period, which poses a significant challenge in terms of energy supply.

- Rédics: The period of energy production is concentrated between 10:00 and 14:00, which means a longer period than in Hegyeshalom (10:00–13:00), but shorter than in Nagylak (9:00–14:00). Peak production can be observed from June to August, when hourly energy production exceeds 4200 Wh, with the highest value in August being 4306 Wh. In September, there is a decrease, and from the second half of autumn, PV production no longer provides enough energy to operate the active protection system.
- Záhony: Energy production is mainly from 9:00 to 14:00, which is the same as in Nagylak. The highest production potential can be observed from June to August, when the hourly energy production reaches 4420 Wh (in August). In September, there is a significant decrease, while from October onwards, PV production no longer provides enough energy to operate the active protection system. Due to the geographical location of Záhony, seasonal fluctuations show a similar pattern as in the other sites studied.

3.2.2 The proportion of energy that can be used to supply the active protection system

In PV-based energy production, it is not only the total amount of produced energy that is a critical factor but also its usable percentage.

- Hegyeshalom: From April to August, the proportion of usable PV energy varies between 37 and 39%, with the highest value observed in April (39%). This can be explained by the high sun position and the more favorable irradiation angles typical of the spring period. In September, the amount of energy available decreases significantly (14%), while from October the PV system no longer provides meaningful energy. Due to the geographical and irradiation conditions, the utilizability of the solar panel system in terms of time is the most limited here, which is particularly disadvantageous for the continuous operation of the active protection system. As a result, the continuous operation of the active protection system from photovoltaic sources alone is not feasible, so additional energy supply solutions are required.
- Nagylak: The highest PV utilizability rates can be observed in July (59%) and August (61%), which provides a favorable energy supply opportunity in the summer period. From March to September, the proportion is between 28 and 49%, but from October onwards, the amount of available photovoltaic energy becomes completely insufficient. The intensity and time course of solar radiation are the most favorable here among the four locations examined, so the opportunities for the independent operation of PV systems are the most favorable here. The results show that PV systems can provide sufficient energy on their own during periods in the summer months, but additional power generation solutions are needed for most of the year to maintain the operation of the active protection system.
- Rédics: The highest usable energy rates can be observed in June (48%) and August (50%). In September, the value decreases significantly (14%), and from October PV production ceases completely. The yields experienced here exceed those of Hegyeshalom but are lower than those of Nagylak. Seasonal fluctuations show that the energy production of PV systems does not provide a continuous supply at this

Table 9 The potential periods of purely photovoltaic energy supply in Nagylak (own editing)

Time of day / Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0–1 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
1–2 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
2–3 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
3–4 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
4–5 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
5–6 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
6–7 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
7–8 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
8–9 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
9–10 (Wh)	0	0	0	0	3764	3843	3858	3926	0	0	0	0
10–11 (Wh)	0	0	0	4043	4136	4220	4288	4363	3851	0	0	0
11–12 (Wh)	0	0	3882	4100	4198	4232	4328	4463	3937	0	0	0
12–13 (Wh)	0	0	3751	3939	4001	4053	4177	4260	0	0	0	0
13–14 (Wh)	0	0	0	0	0	0	3792	3812	0	0	0	0
14–15 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
15–16 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
16–17 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
17–18 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
18–19 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
19–20 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
20–21 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
21–22 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
22–23 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
23–24 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
Sum (kWh)	0.00	0.00	7.63	12.08	16.10	16.35	20.44	20.82	7.79	0.00	0.00	0.00
Proportion of utilizable energy (%)	0%	0%	28%	40%	49%	48%	59%	61%	28%	0%	0%	0%

location either, so additional energy sources are needed for the sustainable operation of the active protection system.

- Záhony: The value in August is 61%, which is the same as in Nagylak. The second highest value (49%) can be observed in May, which differs from the other locations. From October, energy production ceases here too, so alternative energy sources are essential in the winter months. Due to the geographical location, the annual course of solar radiation is more favorable here than in Hegyeshalom, but it does not reach the level of Nagylak. In this case, too, the energy supply of the active protection system with a stand-alone PV system can only be solved seasonally.

Of the examined settlements, Hegyeshalom shows the most limited opportunities, as the PV system is only able to supply energy here from April to September. In the case of Rédics, the period of energy supply is more favorable, but it does not reach the level of Nagylak and Záhony, where the best energy production performance is ensured between 9:00 and 14:00 in the summer months. It should be highlighted that the highest energy production was measured in Nagylak (4463 Wh) in August, while the highest proportion of usable energy in August reached the highest value of 61% in Nagylak and Záhony.

Based on the results, the entire energy supply of tanks cannot be sustained from PV-based sources alone anywhere in Hungary, and even the operation of the active protection systems would be significantly limited. While seasonal variability already limits the energy yield of PV systems in Hungary, battlefield deployment introduces further complications. Weather unpredictability, dust accumulation, shading from surrounding structures or vegetation, and tactical concealment requirements can all reduce effective irradiation and, consequently, power output. In active combat zones, there may also be limited opportunities to optimally position or maintain the PV trailer. These constraints underscore the need to treat PV systems not as standalone battlefield solutions, but as supplementary assets optimized for specific mission phases—particularly stationary, low-visibility deployments. As such, operational planning must incorporate both seasonal and situational unpredictability when integrating renewable sources into armored force logistics.

The above findings resonate with broader energy resilience frameworks that emphasize the importance of distributed, modular, and partially autonomous energy systems in high-risk environments. Within NATO's Energy Security Strategy, increasing attention is given to reducing fuel dependency, enhancing operational endurance, and integrating renewable energy where feasible. Although the standalone PV system analyzed in this study does not enable complete autonomy, its capacity to support critical subsystems during passive deployments aligns with NATO's push toward more sustainable and resilient battlefield energy infrastructures. By identifying realistic operational constraints and integration points, the results contribute not only to technical assessments but also to strategic discussions on energy diversification in armored warfare. To address these constraints, it is essential to improve the system's performance through the integration of energy storage and hybrid energy solutions. Combining mobile PV systems with appropriate battery technologies would offer a more stable, continuous, and mission-relevant energy supply—especially for ensuring the uninterrupted operation of active protection systems during prolonged idle or concealed deployments.

Table 10 The potential periods of purely photovoltaic energy supply in Rédics (own editing)

Time of day / Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0–1 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
1–2 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
2–3 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
3–4 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
4–5 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
5–6 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
6–7 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
7–8 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
8–9 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
9–10 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
10–11 (Wh)	0	0	0	3830	3978	4074	4063	4069	0	0	0	0
11–12 (Wh)	0	0	3762	4050	4119	4232	4240	4306	3806	0	0	0
12–13 (Wh)	0	0	0	3996	4023	4172	4220	4260	0	0	0	0
13–14 (Wh)	0	0	0	0	0	3819	3908	3921	0	0	0	0
14–15 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
15–16 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
16–17 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
17–18 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
18–19 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
19–20 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
20–21 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
21–22 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
22–23 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
23–24 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
Sum (kWh)	0.00	0.00	3.76	11.88	12.12	16.30	16.43	16.56	3.81	0.00	0.00	0.00
Proportion of utilizable energy (%)	0%	0%	14%	39%	37%	48%	48%	50%	14%	0%	0%	0%

While this study did not model hybrid systems in detail, their tactical and operational relevance is significant. Hybrid approaches—combining PV generation with modular battery storage or auxiliary generators—offer increased energy continuity and flexibility, particularly during low-irradiance periods or night-time operations. These solutions could mitigate the temporal mismatch between energy generation and subsystem energy demand, thus ensuring uninterrupted support for critical components like APS and communications. This observation is consistent with recent peer-reviewed studies. For instance, Berardi et al. (2020) demonstrated that combining PV, storage and waste heat recovery in hybrid energy systems for deployable military camps substantially reduces fossil fuel dependence and improves autonomy. Similarly, Mori et al. (2023) [37] showed how hybrid renewable energy–hydrogen hubs at military bases enable near carbon-neutral operation, while Reich & Sanchez (2023) [27] emphasized that PV-battery-diesel microgrids offer resilience under variable weather and mission conditions. In line with these findings, the results of the present study confirm that PV should be regarded not as a stand-alone solution but as a complementary element within layered hybrid architectures tailored to military energy resilience.

The limitation of PV generation to daylight conditions imposes tangible tactical constraints. During night operations, or in environments characterized by extended cloud cover, dense vegetation, or urban canyons, the availability of solar energy may drop to levels insufficient for sustaining mission-critical subsystems. In such scenarios, a stand-alone PV system cannot guarantee the uninterrupted operation of APS or secure communications, which may create vulnerabilities in high-threat engagements. The simulation results confirm that in passive deployment patterns, PV trailers can only provide subsystem autonomy within limited tactical windows defined by daylight and seasonal conditions. In contexts like Ukraine or Gaza, where prolonged engine-off deployments are common, this translates into highly conditional survivability gains—reinforcing the need for hybrid integration to maintain continuity during night operations and adverse weather. These constraints underscore that PV, while valuable, should be viewed as a supplementary contributor rather than a primary energy source, unless coupled with storage or auxiliary power units capable of bridging low-generation periods.

In addition to these operational constraints, panel durability under combat conditions also represents a critical factor. PV modules deployed in armored environments are exposed to shocks, vibrations, dust, and potentially hostile fire, all of which can degrade performance or compromise system integrity. While military-grade solutions increasingly incorporate ruggedized designs and protective encapsulation, these measures add both weight and cost, and their effectiveness under sustained battlefield stress requires further evaluation. Future research should therefore also address material resilience and survivability, as these aspects strongly influence practical feasibility.

For reference, while the price of the BIGLUX Solar Trailer used in this study is not publicly available, comparable mobile PV trailers with a rated power of around 7–10 kW are currently marketed at approximately 35,000–36,000 USD per unit [105]. At the same time, smaller-scale mobile PV towers with similar nominal capacity (e.g., a 7.5 kVA trailer-mounted light tower sold in India [167] for about 8,400 USD) illustrate that lower-cost alternatives also exist, although these are primarily designed for civilian lighting applications rather than armored military deployments [168]. This comparison

Table 11 The potential periods of purely photovoltaic energy supply in Záhony (own editing)

Time of day / Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0–1 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
1–2 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
2–3 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
3–4 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
4–5 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
5–6 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
6–7 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
7–8 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
8–9 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
9–10 (Wh)	0	0	0	0	3821	3862	0	3843	0	0	0	0
10–11 (Wh)	0	0	0	4030	4170	4216	4177	4281	0	0	0	0
11–12 (Wh)	0	0	3800	4095	4227	4257	4230	4420	3786	0	0	0
12–13 (Wh)	0	0	0	3956	4083	4066	4097	4269	0	0	0	0
13–14 (Wh)	0	0	0	0	0	0	0	3809	0	0	0	0
14–15 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
15–16 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
16–17 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
17–18 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
18–19 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
19–20 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
20–21 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
21–22 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
22–23 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
23–24 (Wh)	0	0	0	0	0	0	0	0	0	0	0	0
Sum (kWh)	0.00	0.00	3.80	12.08	16.30	16.40	12.50	20.62	3.79	0.00	0.00	0.00
Proportion of utilizable energy (%)	0%	0%	14%	39%	49%	48%	37%	61%	14%	0%	0%	0%

highlights that the initial capital cost of ruggedized military-grade PV trailers is substantially higher than both conventional diesel generators of similar output and non-military PV trailers, yet the strategic benefits of reduced fuel dependency and logistic risks remain central to their long-term cost-effectiveness.

From a cost-benefit perspective, although initial acquisition costs may be higher than traditional diesel-only systems, hybrid configurations could reduce fuel dependency, simplify logistics, and lower operational risks over time—aligning with NATO's long-term goals for energy resilience and sustainability in forward-deployed scenarios. This observation is supported by Berardi et al. (2020) [21], who showed that hybrid PV-storage systems in military camps reduce fossil fuel reliance and logistical risks, and by Mori et al. (2023) [37], who linked renewable-hydrogen hubs to long-term cost stability. At the vehicle level, Randive et al. (2021) [70] and Lee & Kim (2017) [69] both demonstrated that hybrid drivetrains improve efficiency compared to conventional diesel systems. Together, these findings confirm the cost-effectiveness of hybridization across both stationary and mobile military applications.

Beyond direct cost savings, reduced reliance on fossil fuels also mitigates strategic vulnerabilities linked to supply chain disruptions, contested logistics corridors, and the geopolitical risks of fuel dependency. As highlighted in recent assessments of NATO members, energy costs for defense are not only financial but also operational and security-critical, as dependence on external energy sources can create systemic fragility in prolonged operations. Hybridization, by diversifying the energy portfolio, directly addresses this vulnerability, offering forces the flexibility to operate more independently from traditional resupply routes. Over time, lower fuel transport requirements decrease convoy exposure, which historically accounts for a significant proportion of battlefield casualties. Furthermore, investment in renewable-hybrid solutions strengthens long-term strategic resilience. As fossil reserves diminish and volatility in global energy markets persists, early adopters within NATO can benefit from stabilized operating costs and reduced carbon liabilities. Thus, the cost-benefit equation extends beyond monetary considerations to include survivability, operational endurance, and alignment with NATO's collective energy security strategies [169].

Taken together, these insights highlight that the practical utility of PV technology is less about replacing conventional propulsion energy and more about enabling a layered and diversified energy strategy. Hybrid solutions embody this principle by coupling renewables with complementary systems that ensure mission continuity under a wide variety of conditions. For instance, the combination of solar modules with modular battery packs can secure power for active protection and communication systems during concealed deployments, while auxiliary generators can provide backup in low-irradiance or high-demand scenarios. This layered approach is consistent with NATO's broader emphasis on redundancy, survivability, and reduced logistical vulnerability. Importantly, hybridization is not solely a technical adaptation but also a doctrinal shift, as it redefines how energy is distributed, protected, and prioritized on the battlefield. By reducing reliance on any single energy carrier, hybrid systems enhance both tactical resilience and strategic endurance. Therefore, even though this study did not experimentally model such configurations, the results strongly support their continued development and testing. Embedding PV within hybrid energy networks could represent a decisive step

toward reconciling sustainability goals with the operational realities of modern armored warfare.

4 Conclusions

One of the fundamental challenges of modern warfare is to secure the energy supply of tactical assets, especially by using alternative and renewable energy sources. In military operations, aspirations for increasing energy independence, strengthening environmental considerations and reducing risks in fuel supply chains are increasingly coming to the fore. NATO also pays special attention to environmentally conscious energy use, such as the development of the energy supply of tanks and other heavy military equipment. Consequently, the potential use of solar energy in this area needs careful examination too.

The aim of this research was to investigate whether the power supply of the electrical systems of the Leopard 2A7 + HU tank can be achieved by using PV technology alone. In the course of the research, the power of a solar panel system installed on a trailer suitable for military use was analyzed, considering the solar radiation conditions of Hungary.

The analysis of the data of the electrical systems of the Leopard 2A7 + HU shows that the on-board electrical systems of the tank operate with significant energy consumption, which is covered by either the main engine generator or the APU that serves as an auxiliary power source. Both the main engine generator, manufactured by MTU/Rolls-Royce Solutions, and the Steyr M12 APU can supply a maximum of 20 kW.

The total theoretical maximum energy requirement of all systems is approximately 30 kW, which exceeds the continuously available amount of power of 20 kW. As a result, their simultaneous operation at maximum load can only be ensured by additional energy management solutions. The energy demand can be balanced on the one hand through the temporary power supply from the batteries and, on the other hand, through an internal self-regulating mechanism that dynamically regulates the operation of the individual system components depending on the available power. However, as exact manufacturer data were not available, it is not possible to fully know the details of this, at this time.

The energy requirements of the different on-board systems are different. Some systems, such as optical sights and communication devices, operate with relatively low power consumption, while the stabilizer system and the air conditioning and the NBC system have significantly higher energy needs. In addition, the TROPHY active protection system, which is already installed in the Leopard 2A7A1 and Leopard 2A8 models but is not available in the version used in the Hungarian military, has an energy requirement of 3.75 kW. As this system can be integrated into the Leopard 2 platform, it is a realistic possibility that adding active protection will be part of the future development or modernization of the Hungarian version too.

Based on the above, it can be stated that the electrical systems of the Leopard 2A7 + HU tank are able to operate in an optimized way within the available power limit, (as there is no information about regularly occurring failures of this kind). However, the operation of certain systems may be limited at maximum loads occurring at the same time. In future developments, the possibility of additional energy supply with PV technology may be a particularly promising technology, but further research is needed in this respect.

According to the findings of the research, the PV trailer under investigation is not able to provide the entire electrical system of the tank with sufficient electrical energy, as the energy demand reaches 20 kW at maximum load. In military applications, a reliable power supply is critical, as an overly optimistic estimate can lead to system downtime, which in extreme cases can even cause human and technical losses.

An important result is that while the entire energy supply cannot be provided exclusively from PV sources, the energy required for the operation of the active protection system may be available at certain times. The investigations showed that with the solar radiation conditions of Hungary, the examined PV trailer is capable of supplying the energy for the active protection system, but only for a limited period of time, which significantly reduces the applicability of the technology on the battlefield. The reliance on daylight significantly constrains tactical flexibility and responsiveness, particularly during prolonged or sudden operations that fall outside the optimal solar generation window. Moreover, in combat environments, factors such as adverse weather, dust, terrain obstacles, and concealment requirements can further diminish the actual energy yield. These battlefield-specific variables reinforce the need for cautious integration planning and confirm that PV systems alone cannot be considered mission-reliable under real-world combat conditions. In the light of the data obtained, it can be concluded that it is possible to supply PV energy solely, only in the spring and summer months, and even then, only for a limited time during the day, from 10:00–13:00.

Other limiting factors include the mechanical vulnerability of solar panels, the increase in battlefield detectability, including thermal detectability. The solar panels can reach temperatures of 60 °C during the summer period, which results in significant heat emissions, making it easier to detect the tank by enemies.

The research highlighted that at the current technological level, ensuring the energy supply of the examined tank only from PV energy is not viable, but it can be applied in peacetime for logistical and sustainability reasons. Pure solar energy supply does not currently provide a complete solution, but in combination with energy storage technologies, the reliability of supply can be increased. The combination of solar panels and batteries can be applied to balance energy supply and demand and extend the operating time of the system. Further research in this direction can certainly be promising. Specifically, future research should evaluate hybrid systems that combine PV with modular battery storage or auxiliary diesel generators. Tactical experimentation could also explore drone-assisted PV deployment and recovery, as well as adaptive camouflage materials that reduce the heat signature of solar modules. In addition, material innovations improving panel durability and concealability would increase battlefield robustness.

In conclusion, while NATO's aspirations to promote sustainable energy use in the military are commendable, they face immediate operational limitations—particularly in the case of heavy armored platforms like tanks, where current PV technologies alone are insufficient. Nevertheless, continuous research, development and innovation in the military industry can advance the future military application of renewable energy sources and technologies, with careful consideration and identification of the areas of application suitable for them or their various combinations.

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Author contributions

Henrik Zsiborács: conceptualization, data curation, methodology, supervision, validation, writing—original draft, writing—review & editing. Nóra Hegedűsné Baranyai: conceptualization, data curation, methodology, supervision, validation, writing—original draft, writing—review & editing. András Vincze: methodology, supervision, validation, writing—original draft, writing—review & editing. Farkas Vurai: conceptualization, data curation, methodology, writing—original draft.

Data availability

The datasets used and/or analyzed in the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publish

Not applicable.

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Not applicable.

Competing interests

The authors declare no competing interests.

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