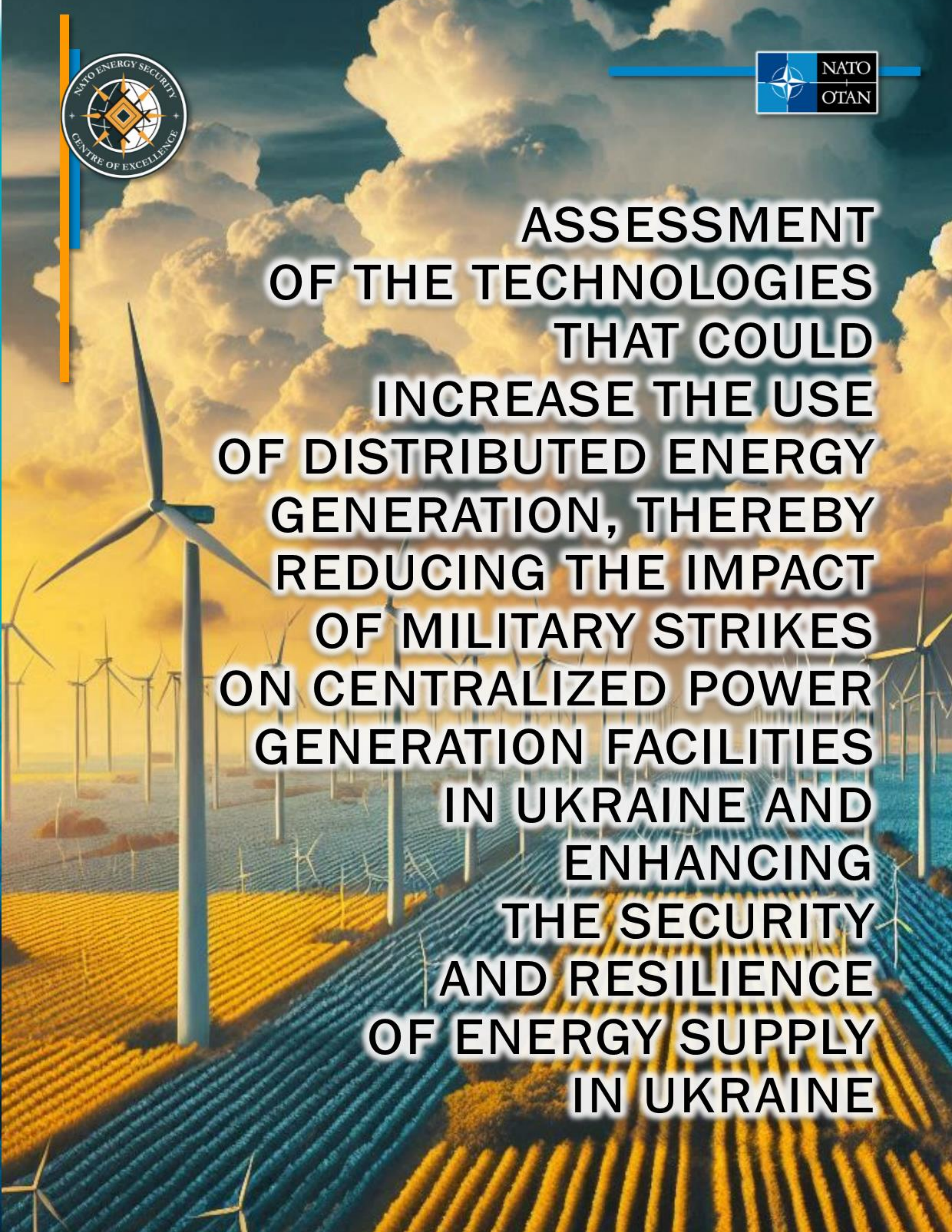

NATO ENERGY SECURITY CENTRE OF EXCELLENCE

NATO
OTAN

ASSESSMENT OF THE TECHNOLOGIES THAT COULD INCREASE THE USE OF DISTRIBUTED ENERGY GENERATION, THEREBY REDUCING THE IMPACT OF MILITARY STRIKES ON CENTRALIZED POWER GENERATION FACILITIES IN UKRAINE AND ENHANCING THE SECURITY AND RESILIENCE OF ENERGY SUPPLY IN UKRAINE

ASSESSMENT OF THE TECHNOLOGIES THAT COULD INCREASE THE USE OF DISTRIBUTED ENERGY GENERATION, THEREBY REDUCING THE IMPACT OF MILITARY STRIKES ON CENTRALIZED POWER GENERATION FACILITIES IN UKRAINE AND ENHANCING THE SECURITY AND RESILIENCE OF ENERGY SUPPLY IN UKRAINE

Research Report

Author

Dr. Arturs BREKIS, *Leading researcher, Institute of Physics of the University of Latvia, Salaspils, Latvia*

Supervisor

Mr Aigars LIEPINS, *Subject Matter Expert, Research Analyses and Lessons Learned Division, NATO Energy Security Centre of Excellence*

NATO ENSEC COE

2024, Vilnius, Lithuania

Table of Contents

1. INTRODUCTION

Europe is now experiencing an unprecedented challenge due to the Russian-initiated military campaign in Ukraine. Russia's war against Ukraine is not primarily about controlling energy resources or infrastructure. In reality, a conventional war includes energy and other non-military aspects. While Russia's cyber-attacks on Ukraine's energy infrastructure have seemingly been ineffective, its intentional large-scale kinetic attacks on energy infrastructure have been a significant aspect of the conflict[1].

Intentional attacks on energy infrastructure during a conventional conflict can serve two primary purposes. Firstly, they can shape the battlefield by depriving armed forces of the fuel needed for vehicles, generators, and other essential equipment or disrupt civilian electricity supplies that military installations depend on. Secondly, they aim to weaken an adversary economically and psychologically by cutting off energy supplies to the government, industry, and civilian populations. These attacks do little to alter the military situation on the ground. Still, they are intended to erode a nation's resilience, demoralize the population, and pressure the Ukrainian government rather than reduce its combat capabilities. Targeting energy supplies to civilians is often viewed as a violation of the law of armed conflict, although the legal case can be more ambiguous than the moral one in the complex context of modern warfare. Such attacks are typically considered to coerce the affected population into making concessions or surrendering, but they may also aim to achieve broader outcomes, such as reducing support in neighboring countries by halting energy exports or causing destabilizing refugee flows.

This approach, which makes extensive use of political, economic, informational, humanitarian, and other non-military methods alongside traditional military actions, and is called "hybrid warfare" should not be regarded as a surprise. The strategy of combining military and non-military tactics to achieve strategic objectives is set out in the "Gerasimov Doctrine" – the Military Doctrine of the Russian Federation, which was approved by it's President on 26 December 2014.

Historically, Ukraine's energy infrastructure was developed alongside the construction of large-scale, high-power electrical and thermal power plants, stations, and substations, most of which were built during Soviet times. This has resulted in a highly centralized energy system in a country with a population of 39,7 million people (2022). Over the two years of war, Russian missile and drone strikes have significantly affected Ukraine's energy sector. The airstrikes, targeting power generation and grid infrastructure and destroying transformer substations and power lines, have caused instability in Ukraine's power system. This affects interconnection flows with neighboring countries and constant, reliable power supply across the country, particularly in regions close to damaged or destroyed power infrastructure.

As the whole world, including Ukraine, transitions towards cleaner energy sources, the central power grid faces reliability, security, and environmental challenges. Enhancing power autonomy is crucial for several reasons:

---

[1] ICDS report War and energy security. Lessons for the future; Tomas Jermalavičius, Veli-Pekka Tynkkynen, Andrian Prokip, Christian Egenhofer, Edoardo Righetti, Arūnas Molis, Priit Mändmaa, Tony Lawrence, Oleksandr Sukhodolia; May 2023.

- **Resilience:** The ability to withstand disruptions, whether due to natural disasters, cyberattacks, or other threats.
- **Military Applications:** Military operations require reliable and secure power sources, especially in conflict zones.
- **Ukraine’s Experience:** Ukraine’s history of energy dependence and geopolitical tensions underscores the importance of autonomy.

In the present work, an overview and analysis are provided for different types of autonomous/off-grid reliable power generation technologies as well as promising future energy sources aligned with the EU green deal and NATO Science and Technology Trends 2023-2043: such as decentralized renewable energy sources, energy storage systems, smart grids and demand response, nuclear reactors for power generation, and alternative technologies. These technologies are aimed to be potentially suitable for future post-war Ukraine’s energy system reconstruction and development, serving as an electrical power infrastructure for both civil and military applications. The scope of this work covers NATO’s priority technology areas that focus on corresponding innovation activities: autonomous systems, energy and propulsion, electromagnetic technology, next-generation communications networks, and artificial intelligence (AI).

2. PROMISING TECHNOLOGIES

2.1 Decentralized Renewable Energy Sources

2.4.1. Solar panels

Solar energy can have different applications:

1) **Solar water heaters** (SWHs) include solar collectors, which merge energy to create heat, storage tanks, and, depending on the system, electric pumps to transfer water between the collector and the tank. Collectors are mounted on a roof, or some raised south-facing area;
2) An innovative solar technology is the **solar comb system,** as it provides both heat and hot water. This system can meet up to 100% of a building’s heating demand, depending on the collector size, the storage capacity, the heat load, and the region’s climate;
3) **Solar thermal power plants** are typically equipped with central receiver systems or parabolic technology;
4) A solar cell is a solid-state device that converts the energy of sunlight (solar radiation) directly into electricity by the photovoltaic effect. The photovoltaic effect is the creation of a voltage (or a corresponding electric current) in a material upon exposure to light.

Photovoltaic panels are made of recyclable materials, typically having in each panel 36/40 PV cells and each array about ten modules. PV cells can be made from various semiconductor materials, such as crystalline silicon, polycrystalline, and single crystalline thin films. These cells convert solar radiation into electricity through their semiconductors. Each cell has an efficiency of around 15%, i.e., it converts about one-sixth of the sunlight it absorbs into electricity.

Advantages of photovoltaic panels:

1) Requires little maintenance;
2) Has no moving parts;
3) Can be installed quickly and in small modules in any place that receives sunlight.

Disadvantages:

1) The installation costs are still quite expensive, but turnover after a few years of usage pays off, as lots of energy is saved. A household, for instance, requires 10-20 PV arrays;
2) Depends on sunlight.

In recent years, the global energy landscape has witnessed a remarkable revolution, with decentralized renewable energy. Unlike centralized power systems, decentralized renewable energy focuses on the generation of electricity through localized renewable sources, as opposed to centralized power plants. Decentralized systems allow the generation of electricity closer to the point of consumption, reducing dependency on long-distance transmission and enabling communities to become self-sufficient.

Grid-connected PV.

When a PV connected to the main electricity grid does not meet all the energy requirements of the house, the electricity produced by the PV is distributed to the grid, while the additional energy requirements are met by the main grid. Two separate meters are installed, side by side, to measure and record the energy produced: one for the PV and the other one for the electricity consumption of the house via the standard connection to the main grid.

The Stand-alone photovoltaic system.

This system is designed to operate independently from the main electric grid and is generally designed and sized to supply specific DC and/or AC electrical appliances. It is usually installed in remote areas where there is no main network or where it is difficult or even impossible to use any other source of power supply. The DC electricity produced is stored in solar batteries and then distributed and used whenever it is needed. This particular solution can be useful for Ukrainian areas, especially in the south of Ukraine, where solar radiation intensity typically is higher than in the north (see Figure 1).

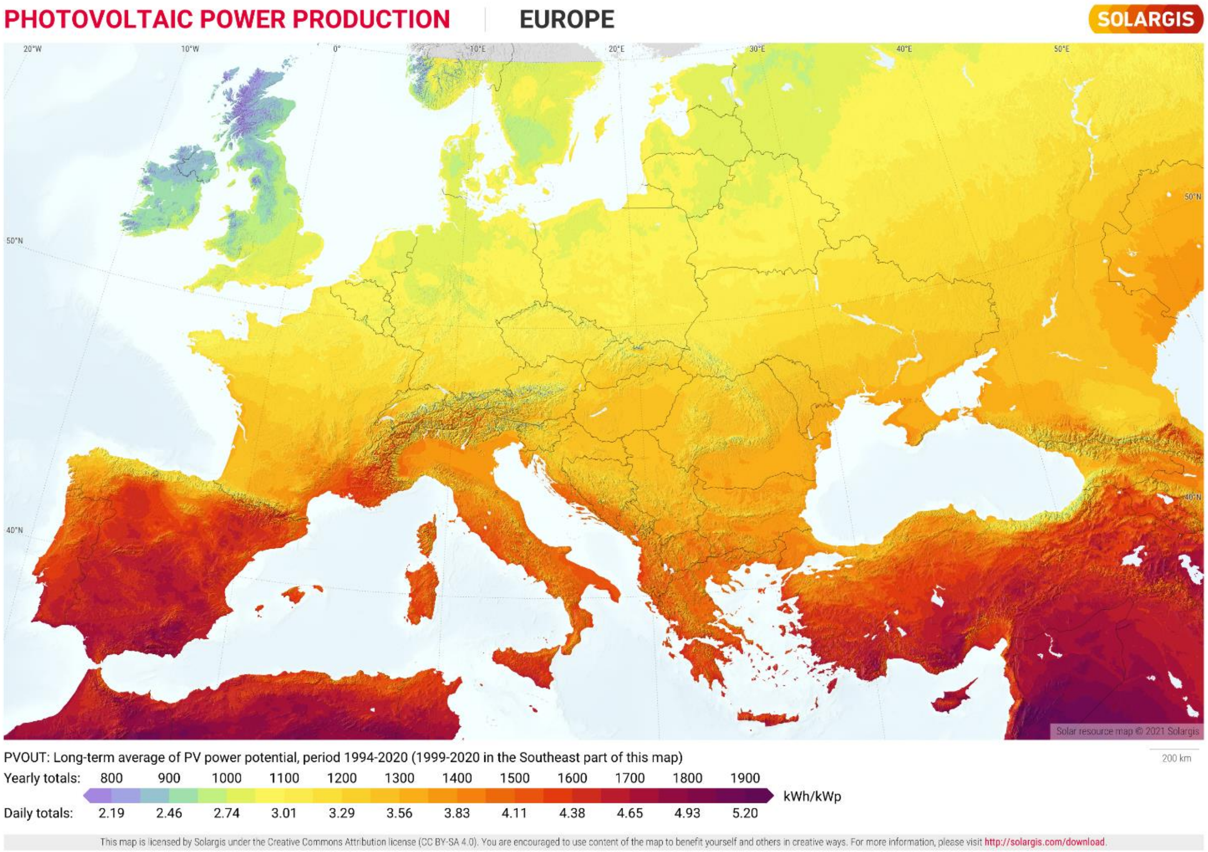

Figure 1. Solar radiation intensity in Europe and photovoltaic power generation potential.

2.4.2. Wind turbines.

Wind power converts wind energy into a useful form of energy, such as using wind turbines to make electricity, windmills for mechanical power, wind pumps for pumping water or drainage, or sails to propel ships. All renewable energy (except tidal and geothermal power), and even the energy in fossil fuels, ultimately comes from the sun.

Wind turbines can rotate on either a horizontal or a vertical axis. Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, which must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator. Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted forward into the wind a small amount.

Vertical-axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. The key advantage of this arrangement is that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable. With a vertical axis, the generator and gearbox can be placed near the ground, so the tower does not need to support it and is more accessible for maintenance. The drawback is that some designs produce pulsating torque. It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is slower at a lower altitude, so less wind energy is available for a turbine of a given size. Air flow near the ground and other objects can create turbulent flow, which can introduce vibration issues, including noise and bearing wear, which may increase the need for maintenance or shorten the service life.

The wind turbines can be located both on the earth and designed for offshore wind farms. In the case of Ukraine, both options are possible since the country has access to the Black Sea. The advantage of building off-shore wind parks is due to higher wind velocities in the sea and the absence of problems with private landowners. At the same time, construction is more complicated and requires more complex and therefore significantly higher investments in infrastructure and may have an impact on marine life and ecosystem.

As a result, due to the higher offshore wind turbine costs, costs for foundation and construction, and more complicated grid connection, initial investment costs for offshore wind power are typically ~ 50% higher. Interconnections are usually implemented using HVDC (high-voltage direct current) technologies. Maintenance costs are also usually higher than those of on-shore wind farms are.

Figure 2 shows the onshore wind potential in the Ukraine - land use but no infrastructural restrictions. The highest potential is in the southern and eastern parts of the country.

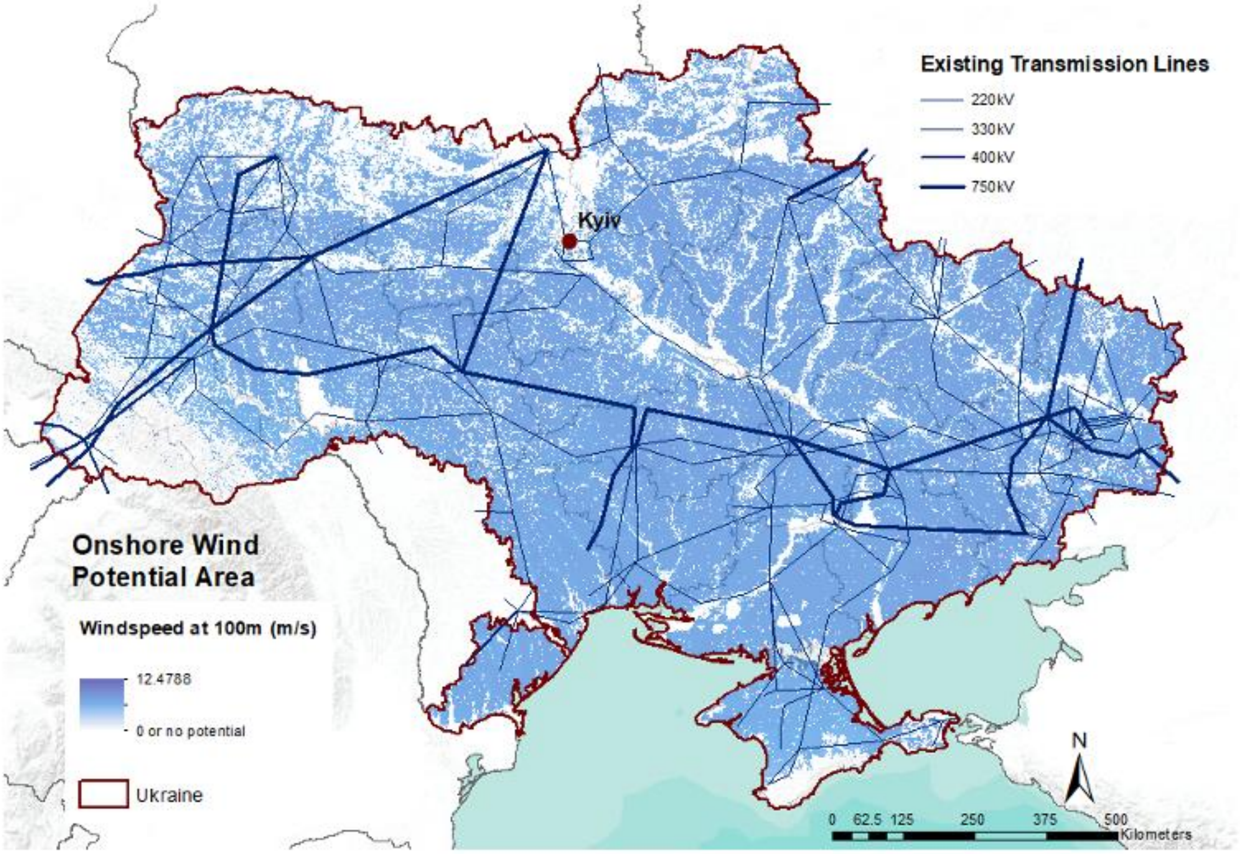

Figure 2. Onshore wind potential in the Ukraine - land use but no infrastructural restrictions.

However, the map in Figure 2. provides a theoretical rather than practical picture of the onshore wind potential areas of Ukraine. In most cases, the land area of the particular country is divided into three sectors: where the construction of wind farms is allowed and supported (1), where the construction of wind farms will be assessed by public authorities but the operator or entrepreneur may face additional costs and compensatory solutions (2), and areas where the construction of wind farms will not be permitted (3).

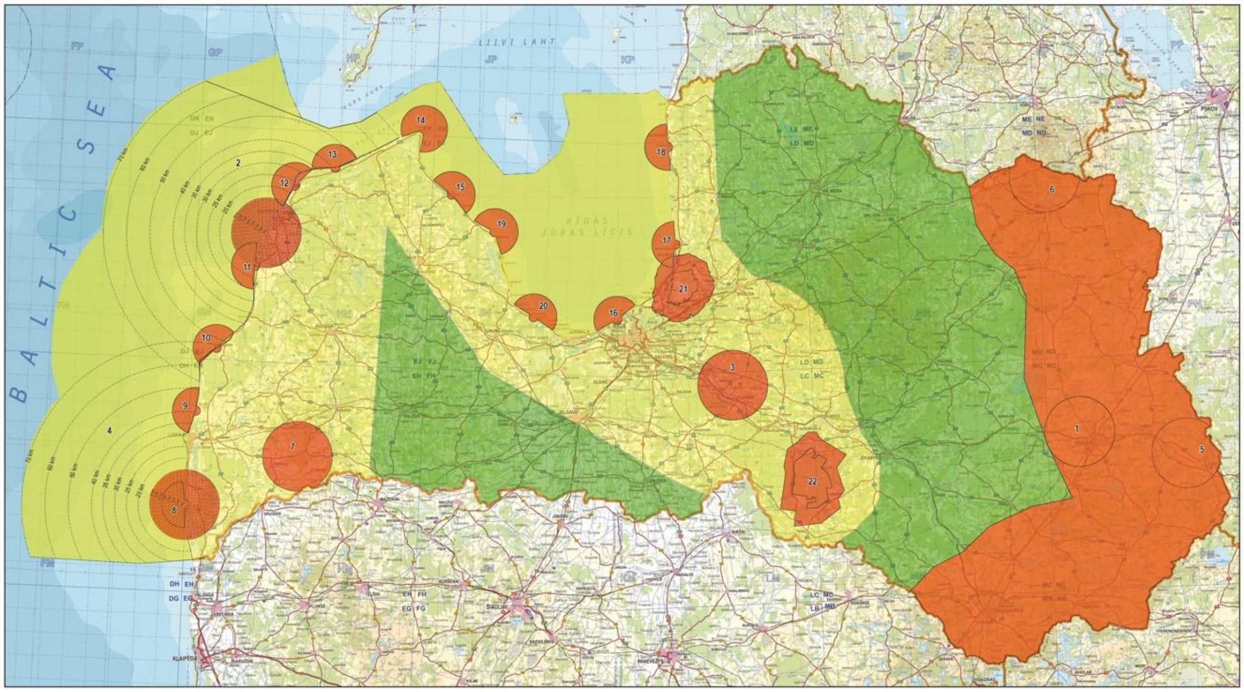

Figure 3. Onshore wind potential in Latvia.

As an example, Figure 3 shows the wind generation map approved by the Latvian Government (2024) The territory is divided into three color sectors. In the green zone, wind farm development is allowed and supported, subject only to the approval of the Ministry of Defence. In the yellow zone, wind farms are discouraged, but the operator will have to take compensatory measures, such as buying new radars. Wind farms cannot be developed in the Red Zone because they would interfere with national defense tasks.

2.4.3. Small-scale hydroelectric power plants.

According to UkrHydroPorject, a local research institute, Ukraine has a major under-developed hydropower resource in its nearly 63,000 small rivers, which accounts for up to 28 percent of the country’s total hydropower potential. Small hydropower plant (SHP) potential is estimated at 2,900 GWh/year. Around 64 SHP (capacity less than 10 MW) were operating in 2011, with a total capacity of only 104 MW, generating around 250 GWh/year. Also about 100 SHP stations that were not operational but could be restored. Many of these stations have been neglected and went into disrepair during decades when abundant supplies of natural gas and other fossil fuels were available both from Russia and Ukraine itself. The potential of small rivers in Zakarpatska, Lviv, and Chernivtsi Regions was barely used.

Currently, large hydropower stations are operating on the cascade of the Dnieper and Dniester Rivers. It is clear that big rivers' potential has been almost fully exhausted with over 4,700 MW of installed hydropower capacity, the majority being large hydro and pump storage stations, eight of which are on the Dnipro River with a total capacity of 4,084 MW and two on the Dniester River with 1,674 MW with 103 hydro generation units installed and operating.

SHP has untapped renewable energy potential in some regions of Ukraine, which could be utilized. Although SHP is generally considered a mature technology, the industry needs continuous infusions of new ideas and technology to ensure that SHP maintains and enhances its contributions to emissions-free, indigenous electricity generation and that hydro facilities operate in harmony with the environment.

The market share of Small hydropower plants in the Ukraine Power System is marginal; in 2017, SHP provided 0.14% of total electricity production, accounting for around 0.2% of the total installed capacity. According to data from the Ukrainian Regulator (NEURC), in 2018, 143 SHPs were operating at the green tariff with a total installed capacity of 96.8 MW. It is important to mention that under Ukrainian law, a small-scale hydropower plant is one with a capacity of 1 to 10 MW.

Based on UkrHydroProject's detailed assessment of two particular regions – the Lviv and Kharkiv studies identified that the Lviv Region has the highest SHP potential, but most of them are not economically and environmentally viable. This region has 135 potential sites for SHP and an estimated total capacity of 137 MW. At the same time, the list of potential SHP in the Lviv Region contains a large number of projects that have a realistically low chance for implementation due to environmental or economic reasons .

The main risks associated with SHP development are:

1) high capital costs and long implementation time from project initiation to start of operation;
2) environmental and social risks, mostly related to large reservoirs to be developed for SHP, and flood risks, which would be environmentally and socially problematic;
3) economic advantages of competing renewable energy resources, wind, and solar power compared to SHP, and
4) requirements to adopt regulations for the construction and operation of SHP.

2.2 Energy Storage Systems.

Energy storage encompasses various technologies, each serving different purposes. Several basic types of energy storage can be used to store energy:

1) Electrochemical systems – e.g., lithium-ion batteries and flow batteries;
2) Mechanical systems – e.g., pumped hydro, compressed air, and gravity-based storage;
3) Thermal systems – e.g., storing heat in solid or liquid materials.

2.2.1. Electrochemical Systems.

Electrochemical systems includes batteries and supercapacitors. Batteries store chemical energy and are used for grid applications and portable devices. Supercapacitors are specifically designed capacitors of storing the large electrical charge. Compared to a battery, a supercapacitor has a fast charge-discharge capacity, can handle low-high temperatures, features low impedance, and is highly reliable.

Battery Energy Storage Systems (BESS) are rechargeable batteries designed to store energy from various sources and release it when needed. BESS balances the electric grid by absorbing excess energy during low demand and supplying it during the peak periods, they enhance grid stability and provide backup power during outages. BESS consists of one or more batteries.

There is a significant shortage of frequency regulation capacity in Ukraine, which is made even worse by damage to critical infrastructure. To cover the lack of frequency regulation capacity, the fastest way is to install new storage batteries, compared to new construction of thermal power units and overhauling existing severely damaged equipment. As a stand-alone equipment, Battery Energy Storage Solutions (BESS) requires less construction work and power plant integration than gas turbine or combined cycle plants.

The new construction of Storage Solutions would also increase Ukraine's frequency control capabilities. Power Oscillation Damping (POD) control will strengthen the interconnector with continental Europe and ensure the security of supply. New BESS construction is needed to unlock the growth of intermittent renewables and help balance the grid. The latest available Ukrenergo's Generation Adequacy Report (Ukraine's transmission system operator) mentions the construction of 700 MW of new battery storage capacities in the near future[2].

The largest private investor in the energy industry of Ukraine – the DTEK group - is an integrated power producer that includes thermal generation, renewables, oil and gas, electricity distribution, and trading and has plans to develop, build, and operate 225 MW / 450 MW-h lithium-ion battery storage plants situated in three locations with a single control center in Ukraine. DTEK group has chosen Honeywell to deploy BESS and supporting technology solutions for a 1 MW-h/2.25 MW-h lithium-ion energy storage system at the Zaporizhya thermal power plant in Energodar, Ukraine. The memorandum for strategic collaboration signed in June 2024 will help to expand DTEC’s battery storage capabilities.

2.2.2. Flywheels.

Flywheel energy storage (FES) works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy. When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of conservation of energy; adding energy to the system correspondingly results in an increase in the speed of the flywheel.

Flywheels are not as adversely affected by temperature changes, can operate at a much wider temperature range, and are not subject to many of the common failures of chemical rechargeable batteries. They are also less potentially damaging to the environment, being largely

---

[2] https://www.energy-community.org/dam/ Battery energy storage systems for Ukraine.pdf

made of inert or harmless materials. Another advantage of flywheels is that by a simple measurement of the rotation speed, it is possible to know the exact amount of energy stored. Unlike most batteries, which operate only for a finite period, for example, roughly ten years in the case of lithium iron phosphate batteries, a flywheel potentially has an indefinite working lifespan. However, where dimensions are a constraint (e.g., under the chassis of a train), a flywheel may not be a viable solution.

FES systems are found in a variety of applications ranging from grid-connected energy management to uninterruptible power supplies. With the progress of technology, there is fast renovation involved in the FES application. Flywheels are sometimes used as short-term spinning reserves for momentary grid frequency regulation and balancing sudden changes between supply and consumption. No carbon emissions, faster response times, and the ability to buy power at off-peak hours are among the advantages of using flywheels instead of traditional energy sources like natural gas turbines. Operation is very similar to batteries in the same application; their differences are primarily economic. This technology is used in various states in the USA and Canada and can be a particularly promising energy storage technology option in the future for Ukraine.

2.2.3. Pumped hydro storage.

Hydropower schemes of the pumped-storage type utilize the flow of water from a reservoir at a higher potential to one at a lower potential. The upper reservoir, also called the head-water pond and the lower reservoir, called the tail-water pond may both be constructed by providing suitable structures across a river. During times of peak load, water is drawn from the head-water pond to run the reversible turbine-pump units in the turbine mode. The water released gets collected in the tail-water pond. During off-peak hours, the reversible units are supplied with the excess electricity available in the power grid, which then pumps part of the tail-water pond water back into the head-water reservoir pump mode.

Excess electricity in the grid is usually generated by nuclear or thermal power plants that are in continuous running mode. This particularly describes the situation in Ukraine, where several nuclear power plants are in operation. However, at night, since the electricity demand becomes drastically low and nuclear power plants cannot switch off or start immediately, a large amount of excess power is available at that time[3]. In Ukraine, such technology is in use in Dniester, Kyiv, and Kanivska (under construction) pumped storage power stations.

2.2.4. Thermal energy storage systems.

The energy storage device that accumulates heat or cold energy to use at a later stage is known as thermal energy storage. Thermal energy storage (TES) device reduces fluctuation in energy supply and demand and ensures reliability and profitability in long-term usage. TES systems usually include materials of high thermal conductivity, high-temperature stability, and negligible volume changes during heat storage. The commonly used solid and liquid sensible heat storage materials are cast steel, cast iron, concreate, brick, rock, ceramic, molten salt, water, and synthetic oil.

---

[3] Water Resources Engineering, IIT Kharagpur, Department of Civil Engineering, Version 2, 2006

In summary, Energy storage systems (ESSs) play a crucial role in enhancing grid stability by storing and converting electrical energy as needed in the following ways:

1) ESSs can store excess energy generated during periods of low demand and release it during peak demand times. This helps balance the supply and demand, reducing the need for peaking power plants and minimizing grid stress;
2) ESSs can provide rapid response to frequency fluctuations in the grid. By quickly absorbing or injecting power, they help maintain the grid frequency within the desired range, ensuring stable operation;
3) Energy storage can provide voltage support by supplying or absorbing reactive power. This helps maintain voltage levels within the required limits, improving the overall power quality and reliability of the grid;
4) During outages or grid disturbances, ESSs can provide backup power, enhancing the ability of the grid to withstand and recover from adverse events such as natural disasters or equipment failures;
5) ESSs facilitate the integration of renewable energy sources like solar and wind, which are intermittent by nature. By storing excess renewable energy and releasing it when needed, ESSs help smooth, out the variability, and ensure a steady supply of clean energy;
6) ESSs can provide various ancillary services such as spinning reserves, black start capability, and load following. These services are essential to for maintaining grid stability and reliability.

Using energy storage systems improves grid stability, can support military bases that are particularly important for Ukraine’s present military situation, and mitigates intermittent output for renewable energy sources.

2.3 **Smart Grids and Demand Response.**

A smart grid is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users.

The primary motivation behind the vision of smart grids is the need to curtail consumption during peak times, alongside green initiatives, renewable energy resource development, and energy efficiency – the assumption being that a better-informed consumer will use less energy. This implies efficiencies primarily come from the better consumer choices enabled by smart meters. Instead, I think the efficiency gains from smart grids are much more wide-ranging. With the interconnected system of sensors and controls, smart grids facilitate automated generation, frequency response, and power routing which are better matched to consumer demand than manual processes allow. Smart grids are indispensable for the successful integration of renewable and distributed energy sources into the electrical network. The concept of smart grids intimately links the energy sector with the information technology and telecommunications sectors. Smart grids enable bidirectional communication between utilities and consumers. Demand response programs allow consumers to adjust usage during peak hours, enhancing grid flexibility.

The smart network is intended to be a self-diagnostic and self-healing network that will continuously send, receive, and process data on the network's state and parameters, and its components, power flows, as well as exchange information with intelligent electronic devices, manufacturers, system operators, traders, and customers.

Artificial Intelligence’s role extends to fault detection and maintenance, contributing to the resilience of smart grids. These intelligent systems continuously monitor the grid for anomalies, rapidly detecting issues and enabling quick responses and maintenance. Peaks in energy demand put utility companies under great strain. Using AI and smart meters in homes and offices can help with scheduling, planning, executing, and monitoring changes in energy demand to ensure that providers can meet them. Doing this can have a major impact on power usage.

Several relevant additional specific concepts can be listed.

2.3.1. Microgrids.

A microgrid is a localized and self-contained energy system that can operate independently from the main power grid (we call this off-grid mode) or as a controllable entity concerning the main power grid (on-grid mode). It consists of distributed energy resources (DERs), such as solar PV plants, wind turbines, storage systems such as batteries, and conventional generators, all integrated and controlled by advanced software tools and communication technologies. They are low-voltage networks with low-power generation units acting as microgenerators, local electricity storage, controllable loads, automatic operation in island mode if the primary power source fails, and automatic synchronization with the network when the primary power supply recovers. This concept could be particularly suitable for future Ukrainian households, equipped, for example, with rooftop solar panels.

2.3.2. Virtual energy companies or virtual electricity market.

A virtual power plant (VPP) is a collection of power-generating units spread over different parts of the same energy grid, connected by a central software platform to make up a larger power plant collectively. VPPs can be made up of combined heat and power assets, renewable generation through wind and solar farms, and battery storage. The units are controlled (dispatched) together through the VPP, but each individual asset can operate independently. In this case, the structure of the electrical grid becomes similar to the structure of the internet network. This means that electricity is bought and delivered to certain points in the network; the supplier freely determines the generation source that is required to meet a specific electricity demand; the operation of the system is ensured by high-level IT and telecommunications solutions, modern power electronics technologies, and electrical energy storage technologies.

2.3.3. Smart metering and modern metering infrastructure (Advanced Metering Infrastructure or AMI).

Advanced metering infrastructure (AMI) is an integrated, fixed-network system that enables two-way communication between utilities and customers. The system collects, stores, analyzes, and presents energy usage data, providing utility companies the ability to monitor electricity, gas, and water usage in real time. It can be considered as the most essential component of the smart grid vision – the first step in implementing the vision of smart networks. Without smart metering, two-way communication with the customer and the customer's energy devices is not possible, and dynamic management of customer loads with variable tariffs is not feasible. Smart metering is a prerequisite for renewable energy resources, especially for the efficient integration of microgenerators into the power grid, as well as, for example, for creating infrastructure for charging electric car batteries and for control.

2.4 Nuclear Reactors for Power Generation.

Ukraine has extensive experience in operating nuclear reactors since the last century, which amounted to 86,2 TWh or 55% of the total electricity generation mix (in 2021). In addition to three research reactors and four shutdown reactors at Chornobyl Nuclear power plant (NPP) under decommissioning process, the country has 15 operable reactors and two under construction at four nuclear power plants, all of which are water-cooled: Khmelnytskyi, Rivne, South Ukraine, and Zaporizhia, the latter currently occupied by Russia. All reactors are dependent on Russian fuel supplies, even though Ukraine had taken steps to move away from such dependence before the Russian invasion. This included a contract with Westinghouse to build a new reactor as early as 2021 Khmelnytskyi. With another contract signed in June 2021, Westinghouse will build more reactors and will supply all of Ukraine's nuclear fuel. In 2019, the percentage of NPP production in the structure of electricity generation in Ukraine was 53.9 %. The high potential of nuclear power in Ukraine's predominantly centralized power system can significantly contribute to decentralization.

Ukraine has already taken several steps over the past five years to develop its nuclear power sector. For example, the Ukrainian nuclear energy company and operator of all the country's nuclear power plants, Energoatom, has signed a cooperation agreement with the US nuclear engineering company "Holtec" for the construction of Small Modular Reactors (SMRs) SMR-160 in Ukraine. It is planned that the first demonstration power unit with the SMR-160 reactor will be completed and connected to the Ukrainian power grid by March 2029. In parallel, the two companies will develop a plan to build and commission an additional 20 SMR-160 power units rapidly. According to the agreement, these reactors and their components will be produced in Ukraine.

According to Ukrainian Energy Minister German Halushchenko, Small Modular Reactors are the best way to replace coal-fired power plants. He also added that the reactors would be used to replace the thermal power plants destroyed in Russian military airstrikes. Thus, nuclear power will help Ukraine not only to decarbonize its electricity and heat sector but also to ensure its energy security.

In June 2022, Ukraine signed an agreement with the US nuclear reactor manufacturer Westinghouse on the construction of nine high-power AP1000 nuclear reactors in the country. Energoatom also wants to obtain permission from Westinghouse to produce AP1000 reactors in Ukraine so that the country can develop the model and even export it. Additionally, in September

2023, Energoatom and Westinghouse signed a Memorandum of Understanding to cooperate on developing and deploying the Westinghouse AP300 SMR in Ukraine. This further strengthens their clean energy partnership. Apart from that, Ukraine is also exploring the possibility of building power units with small modular NuScale VOYGR and Rolls-Royce UK SMRs reactors.

The energy strategy of Ukraine for the period up to 2050 provides for an increase in the capacity of domestic nuclear generation. Therefore, the Energoatom team is actively working to find new sites for construction. The most promising of them is Chyhyrynska, a previously abandoned Chyhyryn NPP project, near the town of Orbita in the Cherkasy region. It is planned to build four new power units using AP100 technology.

However, Ukraine's plans include not only the production and construction of nuclear reactors but also ensuring energy independence by developing the nuclear fuel cycle in Ukraine. Last January, the Ukrainian government approved a plan for the country to achieve uranium independence by 2027, meaning the country will produce all the uranium it needs. In March of this year, Ukraine's energy minister G.Galushchenko announced that even starting from 2026, Ukraine will also produce all the nuclear fuel it needs. In February, Energoatom agreed with Canada's Cameco that the uranium extracted in Ukraine would be transported to Canada, where it would be converted into uranium hexafluoride (UF6), which can then be used for enrichment. The agreement entered into force in April 2023.

2.4.1. Small modular reactors – overview.

Nuclear fission is the process of breaking large atomic nuclei into smaller atomic nuclei to release a large amount of energy. This principle is used in electrical power generation nuclear reactors. From the point of view of power range, SMRs are generally defined as nuclear reactors that are 300 MWe equivalent or less, designed with modular technology using module factory fabrication, pursuing economies of series production and short construction times. Nuclear power is a safe and convenient form of energy that offers reliable, low-carbon power. Many of the NATO member countries, such as France, the USA, and others, have accumulated significant operational experience in various types of nuclear reactors. Ukraine also has been historically using its high-power nuclear reactors as an important contribution to the country's energy balance. At the same time, the possibility of using SMRs is attractive due to its many advantages.

Some of them are:

1) Potentially increased safety margins. Wide possibilities in the use of internal security and passive systems.
2) Simpler and fewer plant systems – potentially lower cost per unit;
3) Potentially easier to build. Simple transport of reactor components to the construction site;
4) Potential for increased use of shared safety systems: personnel and control rooms
5) A long period of operation without refueling;
6) Reduced possibility of uncontrolled proliferation of nuclear materials;
7) Opportunities to use an industrially produced, nuclear-fueled core.

The main disadvantages:

1) Less support from other regulators on technical, regulatory, and operational challenges;
2) Less operating experience – metallurgy, radiation exposure, operational reliability, etc.;
3) Challenges with inspection: At the module manufacturing facility, the reactor is being built not on the site but in the factory.

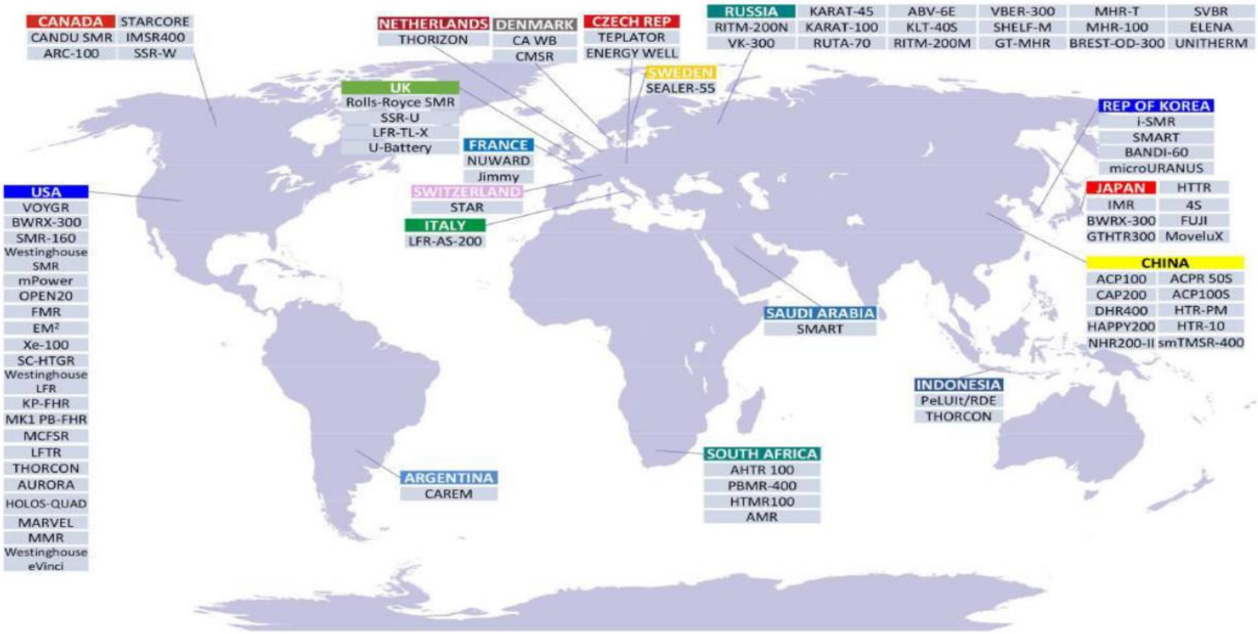

Figure 4. Global map of the SMR technology development[4].

Globally, there are more than 80 SMRs designs at different stages of development across 18 countries. A global map of SMR technology development across the world, with different reactor designs developed by various countries, can be seen, as well as in Table 1. As can be seen (Figure 4), the USA, China, and Russia have the highest number of designs. SMR development is primarily focused on the front-end and passive safety systems. SMR successful deployment also requires a clear understanding of decommissioning and waste management needs.

Table 1. SMR design breakdown (Jan 2024)[5]

Status	**No of SMRs Designs**	**%**
Design Phase	73	88%
Licensing Phase	1	1%
Construction	5 (3 LWRs)	5%
In Operation	4 (1 LWR)	4%
Total	**83**	**100%**

---

[4] S. Magruder, "General introduction to SMR technology", Fundamental Safety Aspects of Water-Cooled Small Modular Reactors, IAEA, Vienna, Austria, 19th February, 2024.

[5] Ibid.

The main parameter that determines the type of reactor that is chosen for construction is the temperature at the exit.

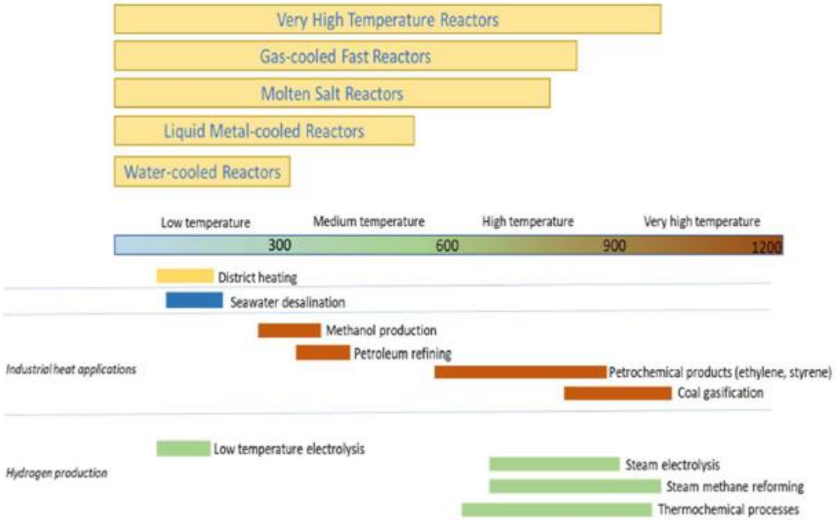

Figure 5. Influence of exit working temperature[6]

In conclusion, constructing a series of Small Modular Reactors as stand-alone energy sources across the country is a way to improve Ukraine's energy security. SMRs can serve military bases, including remote areas, reducing dependency on central grids. SMRs also have possibilities of different alternative uses, including non-electric applications, such as district heating, which is particularly useful for Ukraine's geographical location.

2.4.2. Microreactors.

Nuclear microreactors are very small reactors usually generating less than 50 megawatts electric (MWe)). They are seen as an alternative to small modular - 50-300 MWe or conventional reactors, often around 1000 MWe. By comparison, microreactors can be produced more quickly, and within weeks, transported and deployed to locations such as isolated military bases or communities affected by natural disasters. The summary of different designs and their corresponding power levels is shown in Figure 6[7].

One of the designs for higher power is the Holos-Quad. Holos is a distributable modular nuclear power generator with enhanced safety features optimized to produce affordable pollutant-free electricity and process-heat with the safest melt-tolerant and proliferation-resistant fuels. Holos power conversion system is formed by off-the-shelf components utilized by aviation jet engines and gas turbines commercially available and operational worldwide. This micro-reactor concept is proposed by HolosGen LLC to generate 22 MW with a lifetime of approximately eight effective full-power years for civilian applications. The design is based on a very innovative high-

---

[6] S. Magruder, “General introduction to SMR technology”, Fundamental Safety Aspects of Water-Cooled Small Modular Reactors, IAEA, Vienna, Austria, 19th February, 2024.

[7] Duriem Calderin, Vladan Ljubenov, Anna Clark, Waste and Environmental Safety Section IAEA, Relevant Safety Standards for the Decommissioning, Spent Fuel, and Waste Management of Small Modular Reactors, Interregional Training Course on Safety Aspects of Decommissioning of Small Modular Reactors (SMRs), Vienna, Austria, 19th February, 2024.

temperature gas-cooled reactor concept using four Subcritical Power Modules (SPMs) that fit into one commercial 40-foot transport container[8].

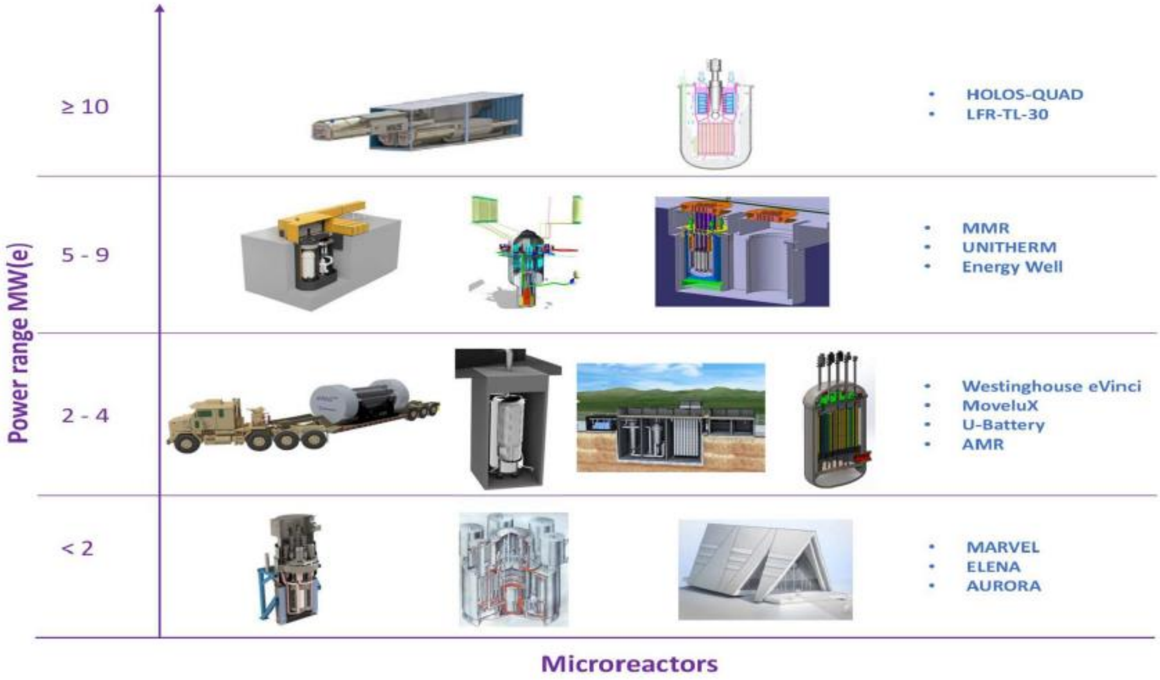

Figure 6. Microreactor designs[9].

2.4.3. Water-cooled SMRs.

Light water SMRs are the most long-standing and most widespread in the world. This means they use normal water as both a coolant and neutron moderator. A distinction is made here between boiling water and pressurized water reactors.

Several water-cooled reactor subtypes can be listed:

1) Pressurized water reactors (PWRs) with forced or natural circulation;
2) Boiling water reactors (BWRs) Loop-type or Integral-type;
3) Heavy water reactors.

Heavy Water Reactors (HWRs) use enriched water, the molecules of which comprise hydrogen atoms that are made up to more than 99% of deuterium, a heavier hydrogen isotope. This heavy water, used as a moderator, improves the overall neutron economy, allowing fuel to be used that does not require enrichment.

---

[8] Advances in Small Modular Reactor Technology Developments — A Supplement to: IAEA Advanced Reactors Information System (ARIS) - 2022 Edition, IAEA, Vienna, 2022.

[9] N. E. Stauff, C. H. Lee, A. Wells, C. Filippone, “Design optimization of the Holos-Quad micro-reactor concept”, EPJ Web of Conferences. 2020, https://doi.org/10.1051/epjconf/202124701005

2.4.4. Modular High-Temperature gas-cooled (HTGR) reactors.

This can be characterized as a relatively mature technology, but in some countries, the fuels, materials, and methods are still being qualified for today's market and regulatory environment. HTGR technology has an extensive base of design, licensing, and operating experience, as well as valuable lessons learned.

For these reactors, ceramic fuel particles, graphite core, and helium coolant offer unique high-temperature working fluid (coolant) capability (700 C to 950 C).

1) High-efficiency power conversion capability: modern Rankine cycle (Eff ~40%) to advanced closed-cycle Brayton (efficiency up to ~47%);
2) High-temperature process steam and process heat capability, typically with cogeneration opportunities;
3) Proliferation-resistant, high burnup fuel cycle with growth potential for advanced fuels and cycles.

Altogether, it reduces environmental impacts and improves nuclear fuel resource utilization. For modular HTGR, as for their safety design and deployment objectives, one of the most important can be mentioned is the possibility to flexibly co-locate with new industry users of nuclear energy. The last one can be specifically important for military applications, such as serving military bases. Altogether, it reduces environmental impacts and improves nuclear fuel resource utilization.

The comparison of light water and high-temperature gas reactors is provided in Table 2.

Table Nr.2. Comparison of Water and Gas reactors[10].

Item	**HTGR**	**LWR**
Moderator	Graphite	Water
Coolant	Helium	Water
Average coolant exit temperature	700-950 C	310 C
Structural material	Graphite	Steel
Fuel clad	SiC and PyC	Zircaloy
Fuel	UO_2 ,UCO	UO_2
Fuel damage time at temperature	UCO – No failures for at least 150h at 1800 C	1260 C
Power density, W/cm^3	4 to 6.5	58-105
Migration Length, cm	57	6
Enrichment %w	8-15	3-4.5

---

[10] Shenoy, A, (General Atomics), History and Evolution of HTGRs, HTGR Technology Course for the Nuclear Regulatory Commission, 2010.

2.4.5. Lead-cooled Fast reactors (LFR).

One of the options to use as a coolant in nuclear reactors is liquid molten metal, in particular liquid lead (Pb) or sodium (Na). Lead does not react with violent exothermic reactions. In particular, Pb has several advantages that contribute to the reactor safety aspects:

1) It can retain almost all fission products;
2) Pb does not burn in air;
3) It does not explode with water;
4) Possibility to open the reactor cover at refueling; negligible dispersion of contaminants;
5) No in-vessel refueling machine;
6) Reduced confinement requirements, including filtering needs.

The operation of LFRs at higher temperatures than LWRs (light water reactors) enhances the opportunities for cogeneration, notably opening a broader range of uses of process heat. A particular example is the possibility of oil shale and oil sand processing, as well as crude oil desulphurization. The last two are typical non-electric applications, where temperatures higher than 400 degrees are necessary, available to LFRs instead of LWRs. Several fundamental technological differences between LFR and LWR are higher fuel burnup, different core materials (e.g., steels vs. Zirconium alloys), different plant layouts (i.e., pool vs. loop), different coolants (i.e., Lead vs. water)[11].

Considering the power ranges, some LFR designs target the microreactor segment with battery-type concepts. In such cases, with the critical mass as the limiting factor, to ensure a very long life core (10 to 25 years of continuous operation), the power density is sensibly lower (even down to ~ 50 W/cm).

Typical LFR SMR are characterized by on-site storage of fuel, as well as the possibility for on-site fuel reprocessing and re-fabrication.

At the same time, lead-fast reactors, due to Pb's high density, have several disadvantages in terms of safety:

1) High overall mass;
2) Seismic risk and buoyancy of immersed components - need to use ballast materials to contrast buoyancy;
3) Need for purification of cover gas;
4) Potential pollution of coolant, concerns about plugging induced by deposits;
5) No possibility of visual inspection;
6) Chemical toxicity of lead (not nuclear safety).

---

[11] V. Sobolev. Database of Thermophysical Properties of Liquid Metal Coolants for GEN IV. Technical Report SCK CEN BLG 1069, SCK CEN (2011). Available online at: https://inis.iaea.org/ collection NCLCollectionStore /_Public/43/095/43095088.pdf

2.4.6. Sodium-cooled Fast reactors (SFR).

Another specific type of fast neutron reactors are the ones cooled by liquid metal, in particular, sodium (Na)[12]. They are characterized by the fact that thermal power generated by fission is induced by fast neutrons. The core is cooled by liquid sodium at 400°C – 550°C. Sodium is not pressurized and has a free liquid surface level in the reactor vessel.

An important aspect of sodium reactors is that they are capable of nuclear fuel breeding. Breeder reactors can constantly replenish the available supply of nuclear fuel by converting fertile materials, such as uranium-238 and thorium, into fissile isotopes of plutonium or uranium-233, respectively. Fertile materials are also non-renewable, but their supply on Earth is extremely large, with a supply timeline greater than geothermal energy. In a closed nuclear fuel cycle utilizing breeder reactors, nuclear fuel could, therefore, be considered renewable. In the world in total, six reactors are operating at the present moment:

- JOYO (Japan, Ibaraki);
- FBTR (India, Tamil Nadu);
- CEFR (China);
- BOR60 (Russia);
- BN600 (Russia);
- BR800 (Russia).

The operation of liquid sodium has to be done very carefully due to its aggressive reaction with water and oxygen. However, due to well-developed sodium technology, these difficulties have been solved effectively with extensive operating experience in the world[13]. This leads to the fact that reactor power and primary circuit management is even easier than LWRs.

In the case of Sodium SMR development in Ukraine, the country could use knowledge extensively accumulated by European countries, such as France, in particular, French Alternative Energies and Atomic Energy Commission CEA. Its R&D research center in the south of France, in Cadarache, has been developing Na technology for decades.

2.4.7. Molten-salt reactors (MSR).

Molten salt reactors are a class of reactors in which a molten salt performs a significant function in the core. Molten salt breeder reactors are characterized by producing more fissile material than they consume; they have a wide range of power scales and can have liquid and solid-fueled variants. Salts can be chloride, fluoride, and mixed halide-based fuel types. A diagram showing the division of MSR is shown below (Figure 7).

---

[12] M.G. Hemanath, C. Meikandamurthy, A. Ashok Kumar, S. Chandramouli, K.K. Rajan, M. Rajan, G. Vaidyanathan, G. Padmakumar, P. Kalyanasundaram, Baldev Raj, Theoretical and experimental performance analysis for cold trap design, Nuclear Engineering and Design, Volume 240, Issue 10, 2010, Pages 2737-2744, ISSN 0029-5493

[13] Ibid.

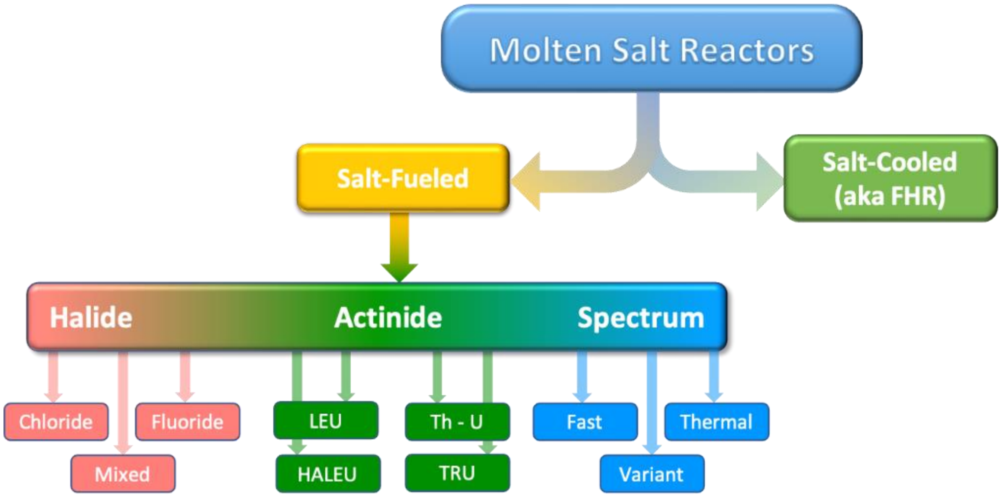

Figure 7. Molten salt reactor variations.

Several aspects make molten salt preferable versus gas, water, or liquid metal:

1) A positive point is that liquid fuel salt cannot be mechanically damaged;
2) They are adequately compatible with nickel-based structural alloys and graphite;
3) Compatibility with chemical processing is also the case;
4) Molten salt has excellent heat transfer.

There has been extensive research done on MSR in the USA during the last century. A significant contribution was made to the aircraft nuclear propulsion program (1946–1961), where the Aircraft Reactor Experiment (ARE) was performed (1953–1954). Another relevant facility was built in the Molten Salt Reactor Experiment (MSRE) in (1960–1969). In the aircraft experiment, they demonstrated the ability to build and operate a high-temperature (860°C), low-power circulating fuel reactor, producing 96 MW-h of nuclear energy. It showed very stable operation due to a high negative reactivity coefficient and demonstrated load-following operation without control rods. An extensive experimental base provided confidence that fluoride salt interactions and operations are adequately understood[14].

2.4.8. Nuclear Fusion reactors.

Research in high-energy plasma physics shows that nuclear fusion - the energy source of the sun and the stars - may provide the cornerstone of a future sustainable energy system. Such power plants would be safe and environmentally friendly. Fusion reactors would have almost limitless supplies of fuel and could be sited anywhere in the world. The international fusion program, ITER (International Thermonuclear Experimental Reactor), will demonstrate the viability of fusion as an energy source. At the moment, this facility is under construction in CEA Cadarache, in the south of France. ITER will be the largest of more than 100 fusion reactors built in the world since the 1950s, with six times the plasma volume of JT-60SA in Japan, the largest

---

[14] D. Holcomb, Molten Salt Reactor Overview, IAEA Interregional Training Course on Non-Water-Cooled Reactors and Small Modular Reactors, IAEA, Vienna, Austria, 23th February, 2024.

tokamak operating today. Fusion is, however, still in the development stage, and it is not expected that commercial power plants will start operating before 2050.

2.5 Alternative Technologies: Thermoacoustic-to-Magnetohydrodynamic Electrical Power Generation.

Ukraine's energy security needs new energy sources that can be used autonomously and independently from the grid. An attractive off-grid solution is proposed by an international group of scientists in the Seventh-Framework European project "SpaceTRIPS." This technology is an electrical generator that has a new working principle. Initially, the main application of "SpaceTRIPS" was focused on autonomous electrical power supply for deep Space missions, powering satellites, space probes, and similar objects. However, future use of this technology can also be extended to terrestrial applications, including military uses. The experimental demonstration prototype was built at the Institute of Physics of the University of Latvia (IPUL), in the city of Salaspils, in the Alkali metals magnetohydrodynamic laboratory.

The "SpaceTRIPS" consists of a unique alternating current magnetohydrodynamic (MHD) generator with liquid sodium as a working body (1) and a thermoacoustic engine (2), which drives the generator by forcing the liquid metal to oscillate in the magnetic field. These two little-known technologies are coupled in one device, which hasn't been done anywhere in the world before[15] [16].

By using the possibilities that thermoacoustic technologies offer, it is possible to obtain liquid metal vibration type movement that is capable of generating consumer-suitable 50 Hz sinusoidal alternating voltage without any mechanically wearing, degradable, and moving parts. The working principle of the TAc+MHD generator is illustrated in Figure 8. The scheme shows the step-by-step energy conversion chain that is the fundamental basis of "SpaceTRIPS."

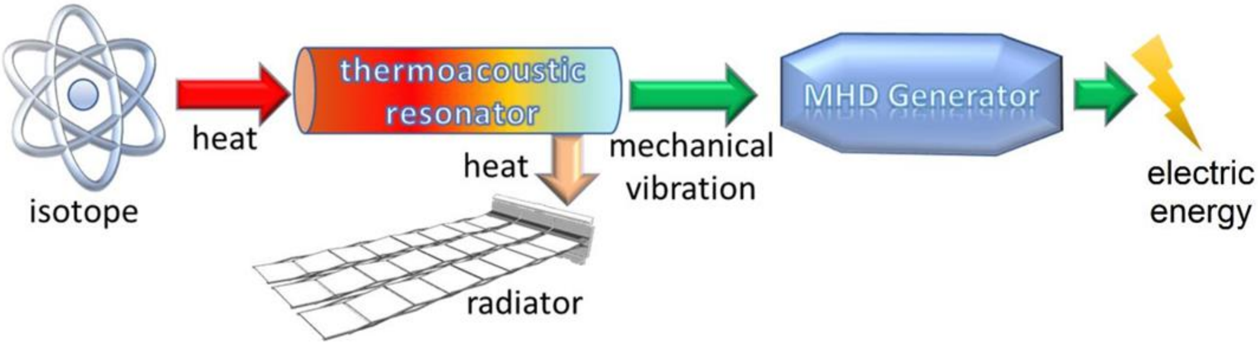

Figure 8. Operating principle of thermoacoustic-to-magnetohydrodynamic generator[17]

The primary energy source for this facility can be a radioactive isotope, the heat produced by which is directed to a specific sound generator – a thermoacoustic engine. The thermoacoustic engine transforms thermal energy into mechanical energy – a sound wave, thus generating pressure oscillations periodically reversing the direction of the liquid's motion. The sound it produces is, in

---

[15] Brekis, A. Freibergs, J.E. Alemany, A. "Space thermo acoustic radio-isotopic power system: Space trips", Magnetohydrodynamics, 2019, 55(1-2), pp. 5–14

[16] Alemany, A Brekis, A. Montisci, A. "A Liquid Metal Alternate MHD Disk Generator." Sustainability (Switzerland). Open access journal, 2023, Vol. 15(16), Nr.12619.

[17] A. Brekis. "Magnetohydrodynamic Generator Driven by a Thermoacoustic Engine", Summary of the Doctoral Thesis, Riga Technical University, 2023.

turn, sent to a specifically designed magnetohydrodynamic generator, producing electricity by using electromagnetic induction. About 0,5 kg of liquid metal is being oscillated in a magnetic field created by radially magnetized SmCo permanent magnets. This movement induces electrical AC current flow in a highly electrically conductive liquid sodium at about 100 degrees C. The pulsating magnetic field produced by this AC current sums by the principle of superposition with the magnetic field produced by the permanent magnets and induces a time-varying electromotive force in the coil of the electric machine (MHD generator). Somewhat similar technologies with MHD power plants were developed in the USA and USSR during the 70's and 80's of the last century. However, the principal difference in this case is, that the prime mover is a thermoacoustic engine. This aspect fundamentally changes the physics and completely changes the operating principle of the machine, by eliminating drawbacks of the conventional MHD power plants developed during the last century, associated with high temperatures in plasma, corrosion, cost, and the need for large superconducting magnets.

Therefore, when a load is connected to the winding, a sinusoidal AC current begins to flow through it. The choice of molten Na is justified by the fact that from all metals, it has the highest electrical conductivity in the liquid state: $\sigma Na = 10.36 \cdot 106\ S/\mathrm{m}$. The high conductivity makes it possible to observe the strongest magnetohydrodynamic interaction. At the same time, the density of sodium at its melting point of 97.8 °C is low: $\rho Na = 928\ kg/m3$. This, in turn, makes it possible to obtain the most favorable conditions for the machine's operation in terms of fluid inertia. This is essential in this case due to the fundamental principle of operation of the proposed technology, which is already based on the acquisition and use of pressure oscillations to create an oscillating fluid flow. However, future use of this technology can also be extended to terrestrial applications, including military uses. Thermoacoustic+MHD technologies are attractive solutions to be used in different applications, not only in Space but also on the Earth. This approach is even more suitable for the Earth's energy sector. This is since the Space microgravity problems and challenges associated with liquid metal-gas free surface interface and hydrodynamic instability problems due to vibrations can be solved a lot easier in Earth gravity conditions rather than in Space. There is only one requirement: heat. This means that present technology can be used in places where cheap and available heat sources are available, which can provide the necessary temperature for corresponding hot heat exchangers in thermoacoustic engines.

Terrestrial applications where the energy conversion principle of "SpaceTRIPS" can be used in Ukraine are (but are not limited to):

1) Electricity supply in energy-starving areas, using Sun heat as a primary energy source instead of radioactive isotopes. In Ukraine's conditions, this approach could be particularly suitable for developing small electrical generation stations across the country. In this case, electrical supply can be produced by using solar heat collectors and parabolic light beam concentrators (see Figure 9.). Combining it with heat accumulation technologies gives the possibility to provide reliable off-grid technology for energy-starving regions, not only during the day but also at night, spending the heat that is accumulated during the day sunlight. This can also lead to convenient electrical power supply solutions where electrification is not developed

at all, or it is complicated or too expensive to provide a connection to the electrical grid, such as in Ukrainian rural areas[18].

2) TAc+MHD power generation can be used as an additional electrical energy source, using residual heat from waste burning. Also, industrial exhaust or waste heat from factories can be used to drive thermoacoustic resonators. In this case, laws and environmental regulations may apply.
3) Emergency electrical supply in nuclear power plants: during a possible nuclear accident, a lot of heat is generated. TAc+MHD energy converted could use this heat to serve as an additional electrical energy generator, for example, to supply power to emergency water pumps for cooling during an accident. Taking into account that Ukraine has its own nuclear power plants, this can be a suitable solution to implement it in the existing or future nuclear reactors.
4) Potential future use of this technology can include military applications. In particular, motorized vehicles could be equipped with low-power portable Thermoacoustic+Magnetohydrodynamic electrical generators, thus serving as an autonomous electrical power supply on battlefields for parts of the army. Combining it with solar parabolic heat concentrators can be a sustainable solution for mobile and autonomous electrical power supply[19].

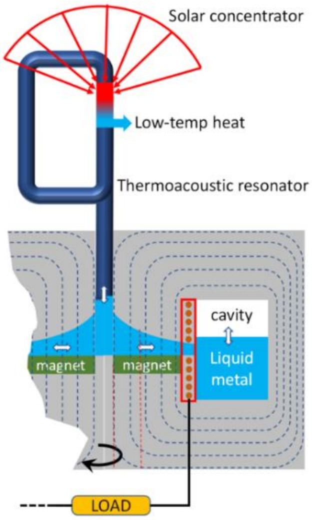

Figure 9. Principle of a thermoacoustic solar engine equipped with an electrical disk MHD generator, suitable for terrestrial applications.

---

[18] A. Brekis, Novel electricity generation technology "SpaceTRIPS": it's potential applications in energy sector and possible impact on economy. University of Latvia 82th Annual International Conference. Section of the Faculty of Business, Management and Economics: Modeling of economic systems and smart transformation- Solving the bottlenecks of energy transition., Latvia, Faculty of Business, Management and Economics of the University of Latvia. Conference report, 2024.

[19] A. Brekis, Novel electricity generation technology "SpaceTRIPS": it's potential applications in energy sector and possible impact on economy. University of Latvia 82th Annual International Conference. Section of the Faculty of Business, Management and Economics: Modeling of economic systems and smart transformation- Solving the bottlenecks of energy transition., Latvia, Faculty of Business, Management and Economics of the University of Latvia. Conference report, 2024.

3. CONCLUSIONS.

The assessment of technologies that could increase the use of distributed energy generation in Ukraine reveals several critical insights and strategic recommendations. The findings underscore the potential of distributed energy resources (DERs) to significantly enhance the resilience and security of Ukraine's energy supply, particularly in the context of ongoing military threats to centralized power generation facilities. **Enhanced Resilience and Security.** Distributed energy generation, including solar photovoltaics (PV), wind turbines, and bioenergy, offers a decentralized approach to energy production that can mitigate the risks associated with centralized power plants. By diversifying the energy supply and reducing dependency on single points of failure, DERs can ensure a more stable and secure energy infrastructure. This decentralization is particularly crucial for Ukraine, where centralized facilities are vulnerable to military strikes. **Technological Advancements and Integration.** Integrating renewables and advanced technologies such as small modular nuclear reactors, microreactors, energy storage systems, microgrids, and smart grid solutions is essential for maximizing the benefits of distributed generation. Energy storage, in particular, can address the intermittency of renewable sources like solar and wind, ensuring a reliable supply even during periods of low generation. Microgrids can operate independently from the main grid during emergencies, providing critical power to essential services[20]. **Economic and Environmental Benefits.** Investing in distributed energy generation not only enhances energy security but also offers significant economic and environmental benefits. The deployment of renewable energy technologies can reduce greenhouse gas emissions, contributing to Ukraine's climate goals. Additionally, the local production of energy can stimulate economic growth by creating jobs in the renewable energy sector and reducing energy import costs[21]. **Policy and Regulatory Framework.** To fully realize the potential of distributed energy generation, a supportive policy and regulatory framework is necessary. This includes incentives for renewable energy investments, streamlined permitting processes, and regulations that facilitate the integration of DERs into the national grid. Policies should also encourage public-private partnerships to leverage private sector expertise and financing[22]. **Community Involvement and Awareness.** Community involvement is a key factor in the successful deployment of distributed energy systems. Raising awareness about the benefits of renewable energy and involving local communities in energy projects can foster acceptance and support. Educational programs and pilot projects can demonstrate the feasibility and advantages of distributed generation, encouraging wider adoption[23]. **Strategic Planning and Implementation.** A strategic approach to planning and implementing distributed energy projects is essential. This includes conducting thorough feasibility studies, identifying optimal locations for renewable energy installations, and ensuring the availability of necessary infrastructure. Coordination between government agencies, energy providers, and local communities is crucial for the successful execution of these projects[24]. **Future**

---

[20] Chapter 3: Enabling Modernization of the Electric Power System Technology Assessment | Flexible and Distributed Energy. Retrieved on 21st of August 2024

[21] A turning point for Ukraine: full-scale energy transition or re-established gas dependency? | Heinrich Böll Stiftung | Brussels office - European Union (boell.org). Retrieved on 21st of August 2024

[22] Ukraine NZW COP28 report 2023.pdf (pnnl.gov). Retrieved on 21st of August 2024

[23] Distributed electricity generation in Ukraine: the risks and opportunities – Ukraine War Environmental Consequences Work Group (uwecworkgroup.info). Retrieved on 19th of August 2024

[24] Distributed Generation in Ukraine - Positive and Negative Results of Energy Decentralization - ZN.ua

Research and Development. Ongoing research and development are vital to advancing distributed energy technologies and overcoming existing challenges. Continued innovation in areas such as energy storage, grid management, and renewable energy integration will enhance the efficiency and reliability of distributed generation systems. Collaboration with international partners can also provide access to cutting-edge technologies and best practices[25].

In conclusion, the adoption of distributed energy generation technologies presents a viable solution to enhancing the resilience and security of Ukraine’s energy supply. By leveraging advanced technologies, supportive policies, and community involvement, Ukraine can build a more robust and sustainable energy infrastructure capable of withstanding military threats and contributing to long-term economic and environmental goals. In addition to the civil sector, small modular nuclear reactors and microreactors can serve military bases and remote areas, reducing reliance on central grids.

---

[25] Development of a distributed energy system in Ukraine - Lexology. Retrieved on 19th of August 2024

Table Nr.3. Advantages and disadvantages of centralized and decentralized power generation infrastructure in the context of system resilience.

1. Advantages and disadvantages of **centralized** power generation infrastructure in the context of system resilience		
Advantages:	Economies of Scale:	Centralized power plants can produce electricity at a lower cost per unit due to their large size and efficiency.
	Simplified Management:	Having fewer, larger plants simplifies the management and maintenance of the power generation infrastructure.
	High Efficiency:	Centralized systems often use advanced technology and can achieve higher efficiency levels compared to smaller, decentralized systems.
	Resource Allocation:	Centralized systems can more easily allocate resources and manage fuel supplies, which is crucial during crises .
Disadvantages	Vulnerability to Attacks:	Centralized infrastructure is more vulnerable to targeted attacks, as seen in Ukraine, where attacks on power plants have led to significant
	Single Points of Failure:	A failure in a centralized system can lead to widespread outages, affecting large areas and many users
	Limited Flexibility:	Centralized systems are less flexible in responding to localized issues or integrating renewable energy sources.
	Long Recovery Times:	Repairing and restoring centralized power plants can take a long time, leading to prolonged outages.
2. Advantages and disadvantages of **decentralized** power generation infrastructure in the context of system resilience		
Advantages:	Increased Resilience:	Decentralized systems are less vulnerable to large-scale disruptions. If one unit fails, the impact is localized, reducing the risk of widespread outages
	Flexibility and Adaptability:	These systems can more easily integrate renewable energy sources and adapt to changing energy demands.
	Reduced Vulnerability to	With many smaller, dispersed units, it becomes more challenging for adversaries to target and destroy critical infrastructure.
	Local Economic Benefits:	Decentralized systems can boost local economies by creating jobs and encouraging local investment in energy projects.
	Environmental Benefits:	They often incorporate renewable energy sources, leading to reduced carbon emissions and a smaller environmental footprint .
Disadvantages	Higher Initial Costs:	Setting up decentralized systems can require significant upfront investment in new technologies and infrastructure.
	Complex Integration:	Integrating decentralized systems with the existing centralized grid can be technically challenging and may require substantial upgrades.
	Regulatory Barriers:	Existing regulations may not be well-suited to decentralized systems, creating legal and bureaucratic hurdles.
	Maintenance and Operation:	Managing and maintaining numerous small units can be more complex and costly than a few large plants.
	Limited Scalability:	While decentralized systems are flexible, they may face challenges in scaling up to meet large-scale energy demands.

4. BIBLIOGRAPHY.

1. ICDS report War and energy security. Lessons for the future; Tomas Jermalavičius, Veli-Pekka Tynkkynen, Andrian Prokip, Christian Egenhofer, Edoardo Righetti, Arūnas Molis, Priit Mändmaa, Tony Lawrence, Oleksandr Sukhodolia; May 2023.
2. https://www.worldometers.info/world-population/ukraine-population/ Population of Ukraine. Retrieved on 16th of July 2024.
3. Decentralized Renewable Energy: A Boon for Remote & Rural Communities | Energy Central. Retrieved on 19th of August 2024.
4. https://solargis.com/resources/free-maps-and-gis-data?locality=europe Photovoltaic electricity potential. Retrieved on 16th of July 2024.
5. https://www.greenpeace.de/publikationen/20240411-greenpeace-report-ukraine-mapping-energy-opportunities.pdf mapping the wind energy opportunities of Ukraine.
6. https://tapportals.mk.gov.lv/legal_acts/2d345d02-ba17-4208-b5a7-ea4aad04fda1. Retrieved on 19th of August 2024.
7. https://documents1.worldbank.org/curated/fr/472871561153957631/The-Executive-Summary-Market-Assessment-of-Small-Hydro-Power-Plants-in-Ukraine.docx Ukraine small hydro summary.
8. https://documents1.worldbank.org/curated/fr/472871561153957631/The-Executive-Summary-Market-Assessment-of-Small-Hydro-Power-Plants-in-Ukraine.docx Ukraine small hydro summary
9. https://www.power-and-beyond.com/supercapacitor-workings-and-applications.
10. https://www.energy-community.org/dam/ Battery energy storage systems for Ukraine.
11. https://automation.honeywell.com/content/dam/automation/en/documents/industries/utility/ia-DTEK-Ukraine-BESS.pdf Honeywell and DTEK energy storage system projects in Ukraine
12. https://dtek.com/en/media-center/news/honeywell-and-dtek-to-collaborate-on-technologies-to-strengthen-ukraines-energy-sect
13. https://web.archive.org/web/20140831005958/http://storage.pv-tech.org/news/canadas-first-grid-storage-system-launches-in-ontario Flywheel technologies.
14. Water Resources Engineering, IIT Kharagpur, Department of Civil Engineering, Version 2, 2006
15. https://www.eesc.lt/en/publication/lessons-of-war-ukraines-energy-infrastructure-damage-resilience-and-future-opportunities
16. https://www.iea.org/energy-system/electricity/smart-grids Smart Grids.
17. https://www.sap.com/resources/smart-grid-ai-in-energy-technologies The Smart Grid: How Artificial Intelligence is powering today's energy technologies.
18. https://www.energy-pool.eu/en/what-is-a-microgrid/ Microgrid
19. https://energyinnovationtoolkit.gov.au/article/case-studies/introduction-virtual-power-plants Virtual power plants
20. https://www.ibm.com/topics/advanced-metering-infrastructure Advanced metering infrastructure
21. https://world-nuclear.org/information-library/country-profiles/countries-t-z/ukraine Ukraine's nuclear energy overview. Retrieved on 12th August 2024.
22. https://icds.ee/en/war-and-energy-security-lessons-for-the-future/ Ukraine-Westinghouse contract. Retrieved on 12th August 2024
23. https://ourworldindata.org/grapher/primary-energy-source-bar Our World in Data. Retrieved on 16th July 2024.

24. https://mind.ua/news/20206817-virobnictvo-elektroenergiyi-z-vidnovlyuvalnih-dzherel-v-ukrayini-zroslo-udvichi-v-2019. Retrieved on 16th July 2024.
25. https://www.neimagazine.com/news/energoatom-and-westinghouse-to-co-operate-on-ap300-deployment-11150438/ Westinghouse memorandum.
26. https://www.world-nuclear-news.org/Articles/Accord-sees-mass-deployment-of-Holtec-SMRs-in-Ukra
27. https://www.world-nuclear-news.org/Articles/Ukrainian-review-of-NuScale-SMR-safety-assessment.
28. https://www.world-nuclear-news.org/Articles/Finland,-Sweden-and-Ukraine-consider-Rolls-Royce.
29. https://world-nuclear-news.org/Articles/Ukraine-planning-for-post-war-nuclear-power-plants.
30. Energoatom is preparing to complete the construction of the previously abandoned nuclear power plant - News of Ukraine - InfoResist
31. https://www.world-nuclear-news.org/Articles/Ukraine-pushes-for-domestic-uranium-supply.
32. https://www.world-nuclear-news.org/Articles/Energoatom-and-Cameco-sign-fuel-and-uranium-agreements.
33. https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors Definition of small modular reactors.
34. S. Magruder, “General introduction to SMR technology”, Fundamental Safety Aspects of Water-Cooled Small Modular Reactors, IAEA, Vienna, Austria, 19th February, 2024.
35. Duriem Calderin, Vladan Ljubenov, Anna Clark, Waste and Environmental Safety Section IAEA, Relevant Safety Standards for the Decommissioning, Spent Fuel, and Waste Management of Small Modular Reactors, Interregional Training Course on Safety Aspects of Decommissioning of Small Modular Reactors (SMRs), Vienna, Austria, 19th February, 2024.
36. Advances in Small Modular Reactor Technology Developments — A Supplement to: IAEA Advanced Reactors Information System (ARIS) - 2022 Edition, IAEA, Vienna, 2022.
37. N. E. Stauff, C. H. Lee, A. Wells, C. Filippone, “Design optimization of the Holos-Quad micro-reactor concept”, EPJ Web of Conferences. 2020, https://doi.org/10.1051/epjconf/202124701005
38. Shenoy, A, (General Atomics), History and Evolution of HTGRs, HTGR Technology Course for the Nuclear Regulatory Commission, 2010.
39. V. Sobolev. Database of Thermophysical Properties of Liquid Metal Coolants for GEN IV. Technical Report SCK CEN BLG 1069, SCK CEN (2011). Available online at: https://inis.iaea.org/ collection NCLCollectionStore /_Public/43/095/43095088.pdf
40. M.G. Hemanath, C. Meikandamurthy, A. Ashok Kumar, S. Chandramouli, K.K. Rajan, M. Rajan, G. Vaidyanathan, G. Padmakumar, P. Kalyanasundaram, Baldev Raj, Theoretical and experimental performance analysis for cold trap design, Nuclear Engineering and Design, Volume 240, Issue 10, 2010, Pages 2737-2744, ISSN 0029-5493
41. D. Holcomb, Molten Salt Reactor Overview, IAEA Interregional Training Course on Non-Water-Cooled Reactors and Small Modular Reactors, IAEA, Vienna, Austria, 23th February, 2024.
42. https://www.jt60sa.org/wp/main-research-objectve/ Advanced superconducting tokamak – nuclear fusion reactor.

43. Brekis, A. Freibergs, J.E. Alemany, A. "Space thermo acoustic radio-isotopic power system: Space trips", Magnetohydrodynamics, 2019, 55(1-2), pp. 5–14
44. Alemany, A Brekis, A. Montisci, A. "A Liquid Metal Alternate MHD Disk Generator." Sustainability (Switzerland). Open access journal, 2023, Vol. 15(16), Nr.12619.
45. A. Brekis. "Magnetohydrodynamic Generator Driven by a Thermoacoustic Engine", Summary of the Doctoral Thesis, Riga Technical University, 2023.
46. A. Brekis, Novel electricity generation technology "SpaceTRIPS": it's potential applications in energy sector and possible impact on economy. University of Latvia 82th Annual International Conference. Section of the Faculty of Business, Management and Economics: Modeling of economic systems and smart transformation- Solving the bottlenecks of energy transition., Latvia, Faculty of Business, Management and Economics of the University of Latvia. Conference report, 2024.
47. https://www.csis.org/analysis/responding-russian-attacks-ukraines-power-sector. Responding to Russian Attacks on Ukraine's Power Sector - CSIS.
48. https://eepower.com/technical-articles/understanding-the-difference-between-distributed-and-centralized-generation. Understanding the Difference between Distributed and Centralized Generation.
49. https://www.atlanticcouncil.org/blogs/ukrainealert/a-decentralized-power-grid-can-help-ukraine-survive-russian-bombardment/. A decentralized power grid can help Ukraine survive Russian bombardment
50. https://marcus.energy/the-benefits-and-challenges-of-decentralized-energy-systems/. The Benefits and Challenges of Decentralized Energy Systems.