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Content

Commander's Corner

Director's Foreword

By **Col. Gytis Kazokas, Director of NATO ENSEC COE**

Welcome to the 21st Edition of *Energy Highlights*, the flagship journal of the NATO Energy Security Centre of Excellence (ENSEC COE).

Throughout 2025, Allies faced disruption and threats to their energy sectors. Fire damage to oil refineries, drone overflights of key infrastructure, and large-scale power outages have demonstrated energy system vulnerabilities. Some of these incidents, such as the Iberian Peninsula blackout, are technical and relate to how we design and build our power generation and distribution systems. But some, like drone incursions, are geopolitical and relate to how our adversaries may exploit the grey zone between peace and conflict. Given the potentially cascading effects of disruption on energy infrastructure – which can affect telecommunications, healthcare, water supply and, ultimately, military readiness - it is a valuable target for hostile actors.

For these reasons, our mission here at the ENSEC COE is as vital as ever. We support NATO, Nations & Partners in addressing resilience, operational energy efficiency, and critical energy infrastructure protection. Over the past year, we have convened an international workshop on Ukrainian energy sector resilience, launched our Coherent Resilience tabletop exercise with a focus on Arctic energy supplies, and delivered our annual multidisciplinary conference. These efforts have helped deepen understanding of risks and strengthen Allied response options. I thank colleagues within our COE and our partners for the significant and continued efforts in carrying out this mission.

Energy security is a shared challenge across industry, government, defence, and academia. It therefore requires insight from diverse perspectives, and Energy Highlights provides a platform for that dialogue. I would like to thank the contributors to this edition for their valuable analysis, and I encourage prospective authors to engage with our Editorial Team - your research and perspectives are welcome.

Thank you for reading, and for your continued commitment to strengthening Allied energy security.

Editorial

By **Dr. Reiner Zimmermann, Head of Research and Lessons Learned Division, NATO ENSEC COE**

This edition of our journal ENERGY HIGHLIGHTS marks the broadening of our editorial base at the ENERGY SECURITY Centre of Excellence. The permanent editorial board is now enlarged to four members, also reflecting the increasing number of article submissions and the wider attention given to our publications.

My name is **Reiner Zimmermann**, an environmental and remote sensing scientist and German Army officer. As the new Head of the Research and Lessons Learned Division at ENSEC, I also took over the role as the Chief Editor of this journal. This is my second term of being delegated by the German Federal Forces to ENSEC and I am proud to support with my expertise all NATO nations and especially the host nation Lithuania in their efforts to improve Energy Security for our civil societies and armed forces.

At this point, allow me to thank my British colleague **Mr. Ben Cook** for having done an exceptional job in handling almost as a one-man enterprise the editing of the past few volumes of ENERGY HIGHLIGHTS. Ben is not only well versed in a variety of energy topics, but also the initiator of the ENSEC Writing Contest which has now turned into a permanent effort. I am happy that he will kindly remain in our ENERGY HIGHLIGHTS team as the Deputy Chief Editor and substantially support our work based on his vast experience and knowledge.

I welcome two new members to our permanent board of editors at ENERGY HIGHLIGHTS: **Ms. Kristina Rimkūnaitė** from Lithuania and **Ms. Marlen Rein** from Estonia. Both are experienced diplomats and currently delegated to ENSEC as Special Matter Experts by their respective Ministries. Mrs. Rimkunaite has a strong background in Energy and Economics and was for several years actively involved in shaping the challenging process of decoupling Lithuania's energy supplies from Russia. Mrs. Rein is an experienced specialist in Energy and Cyber Security and previously served as diplomat for Estonia in European countries.

Allow me to express my appreciation of the excellent work by our public relations officer, **Major Paulius Babilas**, Lithuania, who accompanied our journal as an indispensable help and advisor over the past years. We thank him for his great support and wish him all the best for his new assignment in the Lithuanian Army.

The **new Editorial Team** and the directorate of ENSEC, represented by the Director **Colonel Kazokas**, Lithuania and the Chief of Staff **Colonel Prêcheur**, France, are looking forward to support ENSECs efforts in being the NATO hub of expertise for Energy Security.

We count on your kind interest and participation in this effort as a critical reader and – if interested as contributor – to the ENERGY HIGHLIGHTS journal!

Energy Independent and Efficient Deployable Military Camps

By **Bernard Thonon**

In 2021, the European Defence Fund (EDF) launched a call for projects on "Energy efficiency and energy management." The INDY project (Energy Independent and Efficient Deployable Military Camps) was selected under this call, commencing in December 2022 and concluding in January 2025. It aimed to develop a strategic roadmap towards energy independent and efficient deployable military camps, based on a paradigm shift in energy production, conversion, storage, transport, distribution and final usage. Led by TECES in Slovenia, the project brought together 33 civilian and industry partners from 13 countries and included an End-User Advisory Board of 11 Ministries of Defence, fostering civil-military collaboration on dual-use energy solutions. This article has been prepared with contributions from the INDY steering committee, with Bernard Thonon as the corresponding author: info@indycamp.eu; bernard.thonon@cea.fr.

INTRODUCTION

The UN states that *"Fossil fuels-coal, oil, and gas-are by far the largest contributor to global climate change, accounting for over 75% of global greenhouse gas emissions and nearly 90% of all carbon dioxide emissions"* [1]. Climate change has significant impact on defence activities; it generates weather disasters, displaces populations, exacerbates regional conflicts, and affects armed forces' capacities [1] [2]. Pursuit of carbon emission neutrality may effectively mitigate these risks.

The EU's pledge to become carbon-neutral by 2050 is not the only reason to reduce the carbon footprint of military operations. The transition presents a pragmatic opportunity to improve the operational performance of the armed forces in key ways:

- Securing energy supply and improving tactical autonomy
- Facilitating the deployment of camps and operations
- Reducing logistics burden
- Providing higher electrical capacities at camps and other facilities

The EU is taking action to both reduce greenhouse gas emissions and strengthen the climate change resilience of infrastructure. In 2023, the EU issued a Joint Communication on the Climate-Security Nexus, highlighting the energy-intensive nature of military operations and the necessity to adopt a smart, consistent approach to climate adaptation and mitigation efforts.

In 2021, NATO adopted a Climate Change and Security Action Plan. In 2023 NATO allies confirmed the importance to adapt their infrastructure, military capabilities and technologies, ensuring resilience to future operating environments.

The INDY project is one of the first strategic European projects under the European Defence Fund (EDF) programme, addressing green energy and the resilience of armed forces

By **Bernard Thonon**

Dr. Bernard Thonon holds a degree in mechanical engineering from INSA-Toulouse, France (1985), and a PhD in mechanical engineering from the University of Nancy, France (1991). He is currently the program manager for energy system and network at CEA-LITEN, France. He has coordinated several European research projects on energy technologies (heat exchangers, heat pumps and renewable heating and cooling technologies). From 2014 to 2020, he managed the energy system for industry division. Since 2022 he has been involved in energy projects for defence applications. He is the scientific coordinator of the INDY project, financed by the European Defence Fund, focused on energy system for deployable camps.

Climate	Threat level			Staffing level			Power level			Camp duration			Mil. consumers		
	low	med	high	100	1000	2000	100 kW	5 MW	20 MW	mths	year	years	light	med	heavy
Arctic	X			X			X			X			X		
Temperate			X			X			X			X			X
(Hot) Desert		X			X			X			X			X	
Tropical	X			X			X			X			X		

Table 1: Operational scenario sketch selection matrix

against threats related to energy security, dependence on fossil fuels, supply chain vulnerabilities, and climate change. The two-year research project aimed to develop a strategic roadmap to enhance the energy resilience, independence, and efficiency of future deployable military camps, thereby strengthening the military and operational capabilities of EU armed forces while minimizing their environmental footprint. The INDY goals are to reduce the carbon footprint, improve energy efficiency, increase energy autonomy and reduce logistic burden (figure 1), while guaranteeing safety and being deployable in different geographic regions and climate conditions.

The INDY methodology is the following

- Define requirements for Future Operational Base for 2030 and 2050
- Evaluate energy technology and their capacity to be effectively deployed in military camps
- Analyse security, interoperability, cyber-protection and procurement
- Design the optimal energy architecture and assess its reliability
- Define roadmaps for the deployment of energy efficient military camps in 2030 and 2050

REQUIREMENT FOR FUTURE OPERATIONAL BASES

The initial identification and preliminary analysis of a selected number of operational deployment scenarios provided a foundational understanding of current and future aspects of military operations expected to be relevant for future Energy Efficient Military Camps (EEMC). The project's objective was to look at two analyses, one top-down analysis of the 2030 and 2050 armed forces Future Operating Environment, and one bottom-up analysis of typical camp operational scenarios today and in the future (to the extent predictable), in order to derive the meaningful "key operational aspects" for EEMCs in 2030 and 2050.

Four different case studies representative of different scenarios, sites, types of activities and localisations, and with different climatological conditions, have been in-

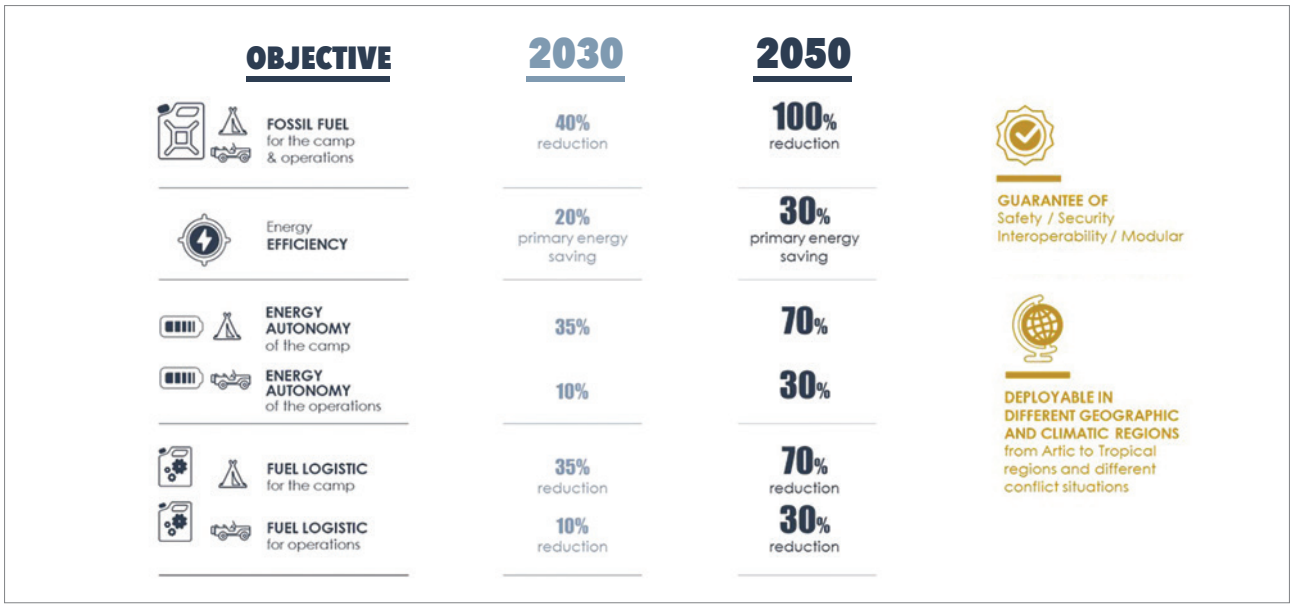

Figure 1: INDY objectives

vestigated during the course of the project. These case studies aim to be both as generic as possible, so as not to predetermine subsequent in-depth analyses in the technical work packages, and as specific as necessary to meaningfully reflect the main operational aspects of an EEMC covering the four main climatic conditions. In the following sections the case studies are defined according to the climate condition; Arctic, Temperate, Desert and Tropical. The key parameters are summarised in table 1.

TECHNOLOGIES FOR ENERGY EFFICIENT MILITARY CAMPS

The energy supply of future military camps is facing a significant change. Until today, military camps have been operated with diesel generators, which are reliable and powerful, but pose considerable logistical challenges as well as environmental disadvantages. In the future, extensive electrification of camp systems and greatly increased use of renewable energy sources are anticipated. The project undertook a comprehensive overview and ranking of energy sources, energy conversion, and energy storage technologies, provided below. This assessment is built upon the operational scenarios, forming a solid foundation for evaluating the various technologies. Efficient energy and vehicle use in military camps for 2030 and 2050 has also been studied and analysed.

The key findings for each technology group are as follows:

- **Electricity Generation Technologies:** Solar photovoltaic (PV) panels emerged as highly suitable for military applications due to their high Technology Readiness Level (TRL), ease of deployment, and low capital expenditure (CAPEX). Wind energy can complement solar PV, particularly in temperate climates, but faces feasibility issues in environments where visibility and maintenance challenges are critical. Small modular nuclear reactors (SMRs) and geothermal energy were also explored, but each comes with unique challenges such as high CAPEX, maintenance complexity, and safety concerns in hostile environments.

- **Electricity Storage:** Lithium-Ion battery variants are expected to be the most promising electricity storage solution until at least 2030. However, in the period 2030-2050 these are to be supplemented by more promising systems such as Lithium-Sulphur and Sodium-Ion batteries. Particularly in the arctic scenario, supercapacitors are expected to be the most advantageous storage solution.

- **Waste to Fuel:** While waste-to-fuel technologies offer potential for additional fuel production, for smaller camps the limited waste generation in military camps reduces their relevance. For larger camps, waste to gas or waste to fuel solutions could be deployed.

- **Combustion Engines, Fuel Cells, and Other Heat-to-Electricity Technologies:** Diesel engines and variable speed generators are the most practical for immediate deployment, though their reliance on fossil fuels conflicts with long-term sustainability and independent operation goals. Microturbines and gas turbines offer greater flexibility for renewable fuel use but come with higher CAPEX. Fuel cells, while portable, are less reliable in harsh conditions. Hydrogen internal combustion engines with combined heat and power has considerable potential for producing both heat and electricity in adjustable ratios and is an established technology expected to be readily available in 2030.

- **Heating and Cooling Technologies:** Direct electric heating is the simplest and most modular solution but is less efficient. Heat pumps, particularly compression heat pumps, offer a more energy-efficient option but require higher CAPEX and maintenance. Solar thermal collectors and PV-Thermal systems were examined as well for their potential in providing hot water and supplementary heating.

- **Thermal energy storage:** Thermal energy storage is particularly important when there are several different sources of heat/cooling from renewables and waste heat. Some technologies (e.g. water, paraffins, eutectics, ice) are already on high TRL and not much improvement is expected in the next years. Newer technologies and materials continue to be developed and optimized, potentially shifting the relative performance and cost-competitiveness of the different options.

- **Efficient energy use:** Passive and active measures are widely applicable even when microgrids are not used and can lead to significant energy savings in various areas of EEMCs. These savings can be achieved through the implementation of new materials and technologies (tent-shelter insulation, shading, LED lighting…), the strategic integration and wise usage of different technologies, and the optimal placement and use of buildings, shelters, tents, and their components alongside well-defined procedures. The results indicate that individual measures can deliver local energy savings of over 50% for specific applications in the different camp scenarios. The passive and active measures represent an additional degree of freedom for enhancing the overall efficiency of EEMCs.

Hydrogen, in addition to being an energy carrier, is also a transportable means of storing energy in large quantities over long periods. Manufactured from renewable energy and water electrolysis, hydrogen is also a low-carbon energy source. Nevertheless, in the short term, its price means that in both military and civilian sectors, it must be reserved for very specific, high added-value applications that cannot be directly electrified. However, future cost reduction and advancements in the civilian sector such as improvements in efficiency - the recovery of oxygen and waste heat from electrolysis, the reuse of water generated from fuel cells - could increase the attractiveness of hydrogen.

Even given restricted military use, INDY studies clearly show that in the short term, there will not be enough surplus renewable energy production (solar and wind) inside military camps to consider producing a massive quantity of hydrogen there. The hydrogen used in military camps will therefore have to be produced elsewhere and delivered in the same way as standard fuels, or otherwise produced in limited quantities for specific needs (non-stationary applications).

If it is not possible to mass-produce hydrogen locally from renewable energy, the hydrogen must be produced from grid electricity, which is generally neither reliable nor abundant in the regions where military camps are located. Its carbon impact therefore depends heavily on the local energy mix. The European countries where electricity has the lowest carbon content (Sweden, Norway, France, in particular) are the most appropriate for producing hydrogen for future military camps. This hydrogen then has to be transported to the camps. For limited uses, the study shows that the logistics of hydrogen in its compressed gas form are most relevant.

In the longer term, there are two main reasons for considering hydrogen in a military camp: (1) to increase the camp's resilience by adding an additional source of energy (especially for long term energy storage) and (2) to reduce the camp's carbon impact by using decarbonised energy.

DESIGN OF ENERGY EFFICIENT MILITARY CAMPS

Energy Efficient Military Camps integrate efficient technologies, renewable energy sources, advanced energy storage systems, onsite e-fuel production (e.g., hydrogen), and improved operational procedures to enhance efficiency, reduce fuel imports, increase energy autonomy, and minimize greenhouse gas (GHG) emissions. Incorporating intermittent renewable energy sources and a broader range of technologies unconventional for the defence sector significantly increases system complexity. This complexity, along with potentially conflicting objectives, makes simulating EEMCs a multi-criteria problem that requires a simulation tool to determine optimal technology selection, layout, sizing, and dispatch strategies.

INDY simulations analysed and determined optimal energy system topologies for four distinct EEMC use cases located in temperate, tropical, arctic, and desert climates and varying in operational duration, size, environmental conditions, and energy demand. The simulation results for each use case revealed insights into technology and sizing configurations which could achieve overall camp energy objectives such as reduced GHG emissions, increased energy efficiency, increased energy autonomy, and reduced fuel logistics burden.

Remote deployable military camps were simulated using PERSEE, an optimal design and control tool for complex energy system developed by the CEA [3]. The tests aimed to determine the optimal energy asset scope, specific technologies, and deployment methods. While simulations were conducted separately for each use case, the methodology utilised remained consistent throughout. Simulations were structured to meet specific constraints, including reduced GHG emissions, reduced reliance on imported fuels, and increased energy self-sufficiency, all while holding to the main objective of minimising costs. Three scenarios were developed to explore the feasibility of potential energy system setups to address the camp objectives: the Legacy Scenario, the 2030 Scenario, and the 2050 Scenario.

In the Legacy Scenario, the energy production inside field camps is currently achieved by using diesel or F-34 fuels. Currently, mainly diesel generators are used to provide electricity to the camp. The allocation and size of diesel generators can vary depending on the design of the field camps. Although the electric load should be between

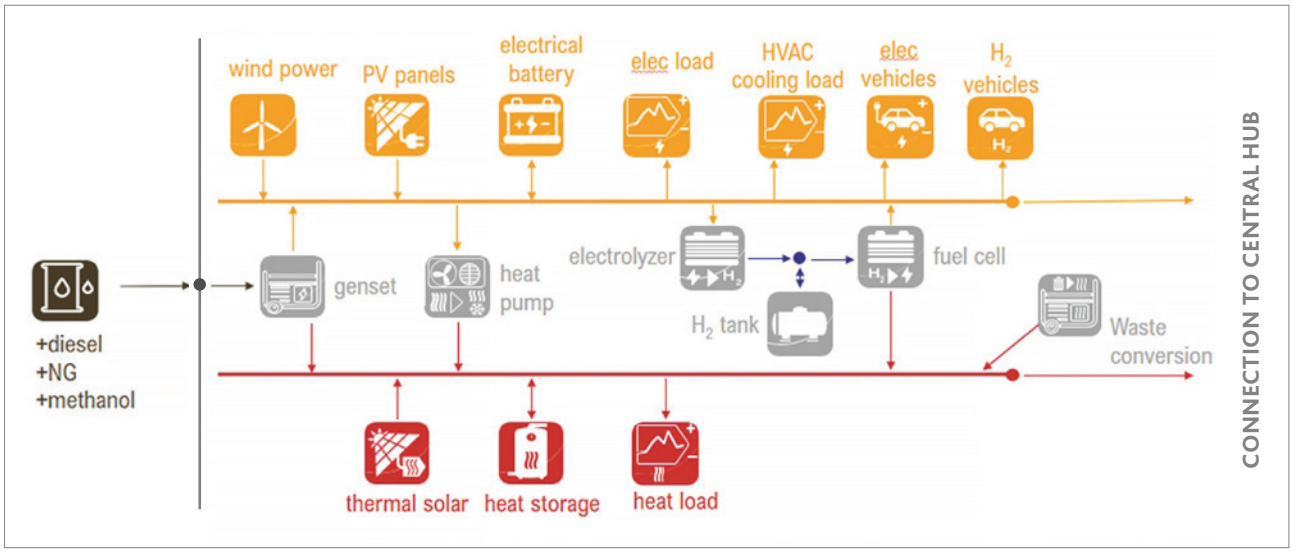

Figure 2: Camp energy architecture for the Temperate case (2030 scenario)

50-100% of the full generator capacity, the generators can go down to very low percentages (e.g. <10%) resulting in an inefficient use of the fuel. The inefficient use is mainly resulting from the non-availability of smaller sized diesel generators at the expected time. Co-generation of heating or cooling with the same Genset is also not used.

However, critical equipment such as containers related to computers/servers/communication can often have a dedicated separate bigger sized diesel generator providing the needed electricity. A second diesel generator with the same size is usually available in sequence for redundancy.

Other electrical equipment in the camp main area is directly connected to smaller sized diesel generators allocated for either one or more tent(s)/container(s).

In some rare cases, electricity is available from closely located infrastructure. However, this is not usual. The heating needs can also be covered by using F-34 in heaters or HVAC systems. For accommodation in arctic cases, F-34 fuelled primus stoves are also an option.

For the Legacy Solution, 100% of the energy is provided by fuel imported to the camp. The energy autonomy, defined as the share of local energy production, is equal to 0%.

In the following, we will present results for the Temperate and Arctic cases. Temperate conditions for a front base of 2000 staff is a widely representative case, while the Arctic case for a forward tactical camp of 50 soldiers is the most critical case.

For temperate conditions, the 2030 Scenario introduces advanced energy components that, while uncommon in the defence sector, are commercially available. Incorporating a diverse energy mix and a centralised microgrid setup achieves all camp energy objectives while strengthening resilience. The topology is presented in Figure 2 where we can see the additional technologies considered in the simulation as well as the use of a central microgrid.

The 2030 scenario results for the temperate use case achieves all camp objectives, namely fossil-fuel reduction, energy efficiency, energy autonomy, reduced fuel logistics, and a single-fuel strategy relative to the legacy scenario. Results in comparison to the legacy scenario for CAPEX and OPEX, as well as a representation of camp operation in terms of fuel usage, CO_2 emissions, energy efficiency, and component control strategies can be seen in figure 3. Rooftop PV is adopted as much as possible, covering all available area. For heating, combined heat and power gensets are installed in parallel with conventional gensets. Energy storage includes heat storage and batteries.

For Arctic conditions: The energy concept of the 2030 scenario consists of a central microgrid interconnecting all units. The simulation results for the 2030 scenario will be presented for a 12-month simulation, with a progressive comparison to the legacy scenario results. A simulation was done for the 12-month 2030 scenario with only a CO_2 constraint of 40%. The results have shown that most of the goals can be reached with a 2% increase in total costs. However, the camp achieved just 13% energy autonomy against a goal of 35% by 2030 in this simulation. To achieve all INDY objec-

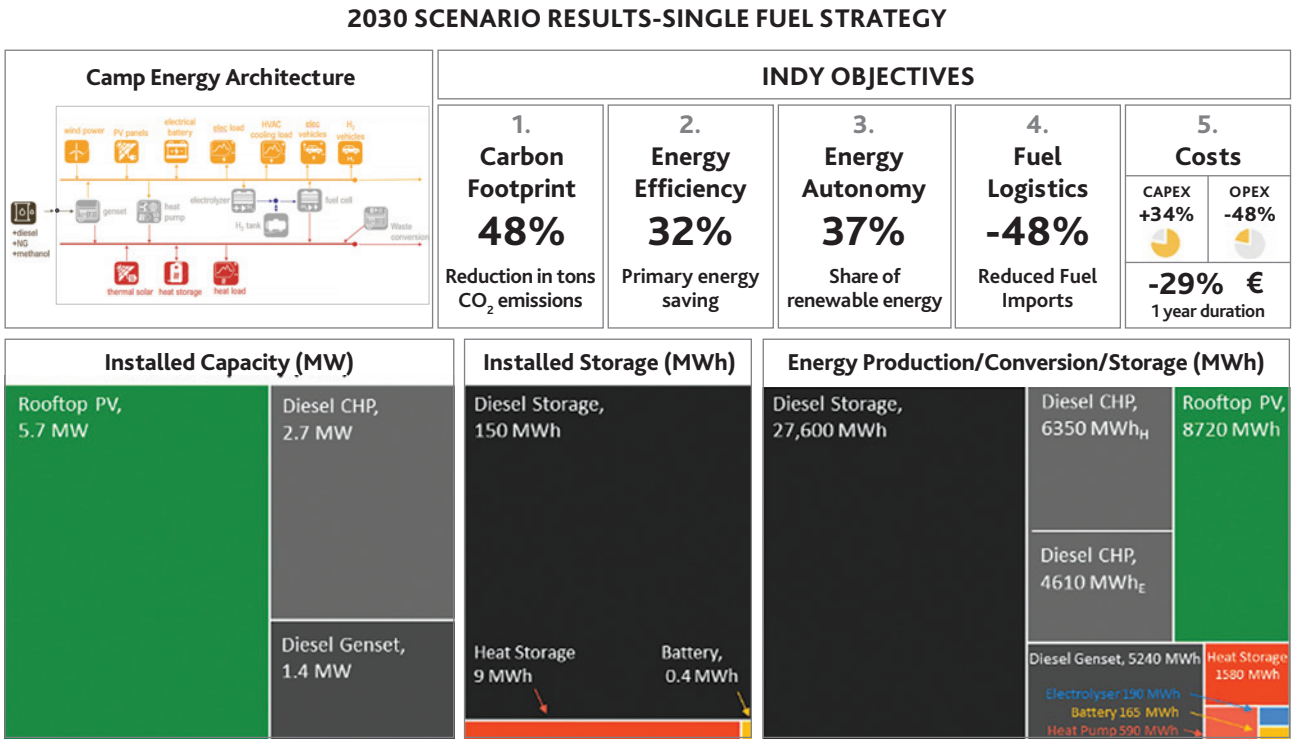

Figure 3: Camp energy solution for the Temperate case (2030 scenario)

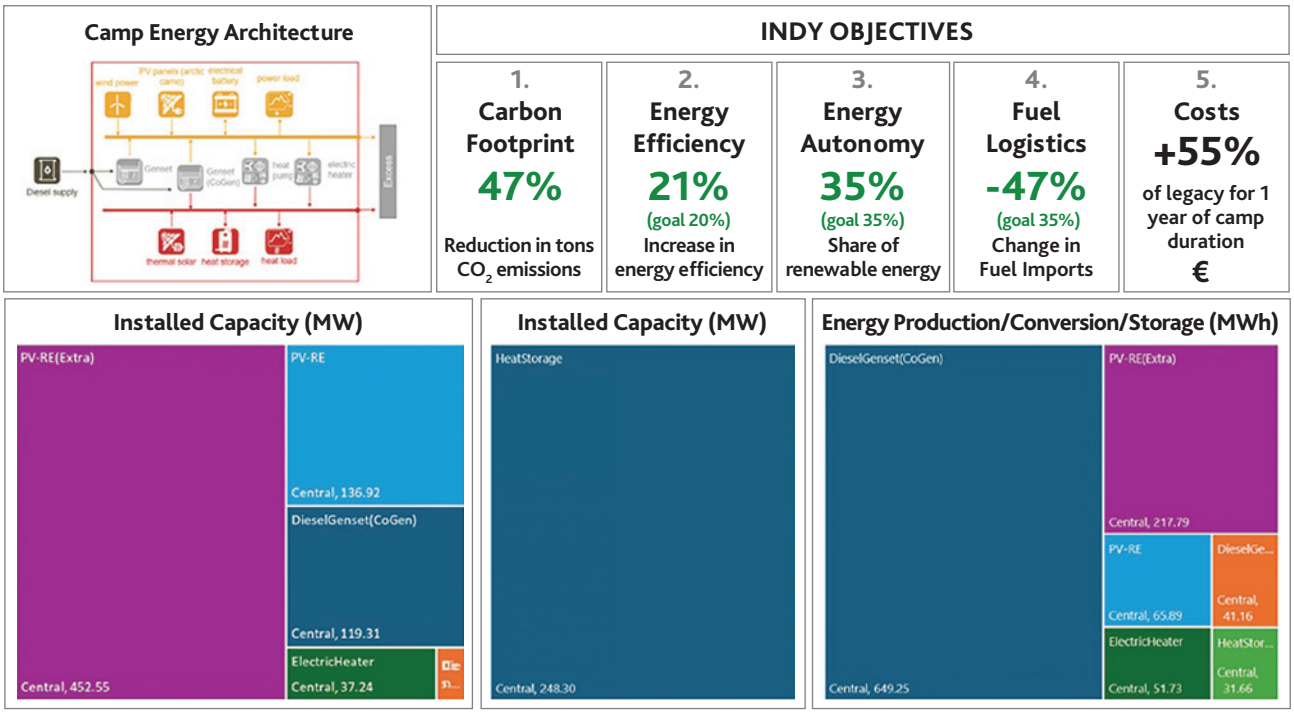

Figure 4: Final camp energy solution for the Arctic case (2030 scenario)

tives, an additional constraint of 35% was imposed for all following results independent of camp duration (Figure 4).

It can be observed that total space required for PV is 3,233 m² with a capacity of 452.55 kW. But, wind turbines, solar thermal collectors and heat pumps are not installed. A negligible small battery is installed, not visible in the results since it is used for only one hour during the whole year. Since the main cost share in the legacy scenario resulted from fuel costs, the use of renewable energy sources results in a 55% cost increase for a camp duration of 12 months. This is due to the distribution of the solar irradiation during the all year, which cannot provide sufficient PV energy for a high number of hours. The PV panels are underexploited.

In conclusion, the simulations confirmed that by 2030 (table 2), EEMCs can achieve the defined objectives, with at least a 40% reduction in carbon footprint, a 20% increase in energy efficiency, a 35% improvement in energy autonomy, and a 35% reduction in fuel imports. These objectives can be achieved through centralised microgrids, high integration of renewable energy (especially PV), and enhanced energy storage systems. While the proposed solutions involve higher initial CAPEX, significantly lower OPEX ensures overall cost efficiency. This cost advantage becomes even more pronounced over extended periods of operation for the EEMCs. By 2050, complete fossil fuel independence is achievable, with renewable energy providing the majority of camps' energy needs. However, this requires addressing the challenges of land requirements and costs substantially higher than those of legacy systems.

LIFE CYCLE, CYBER-PROTECTION, INTEROPERABILITY, SAFETY AND PROCUREMENT

The project analysed the raw material criticality, specifically availability, dependencies, and possible sources. The overall CO_2eq emissions and other environmental impacts of the entire energy system life cycle were evaluated based on overall system layout and subcomponent definitions and specifications as delivered by other work packages. The potential to reduce environmental impact with novel energy conversion technologies, though potentially substantial, is constrained by the need for a steady energy supply to critical loads. The results are focused on GHG emissions, but other indicators of impact on the environment, human health, and resource availability were briefly assessed. As a result, we can conclude that the increase in renewable energy systems in military camps can lead to a significant reduction in GHG emissions and in dependency on fossil resources, but also poses new challenges such as an increased dependency on critical raw materials and a shift of the burden to other impact indicators for environment, health, and resource availability.

Interoperability is undoubtedly one of the most relevant questions in making this new energy infrastructure possible. Resolving interoperability in all its facets will require an enormous amount of effort and resources. This conclusion, alongside the studies carried out, motivates the creation of standards by which both known and not-yet-identified needs can be met. From this point of view, always targeting alignment with NATO guidelines, INDY has proposed adopting a model based on predefined compo-

Scenario 2030	Solution 2030	Carbon Footprint	Energy Efficiency	Energy Autonomy	Fuel Logistics	Cost
		Reduction of CO_2 emissions	Primary energy savings	Share of renewable energy	Fuel importation	Cost of ownership for 12 months
Temperate	**Rooftop PV Diesel CHP Energy storage**	48%	32%	37%	-48%	-29%
Arctic	**Rooftop and field PV Diesel CHP Electric heater**	47%	21%	35%	-47%	+55%
Desert	**Rooftop PV Diesel genset**	40%	45%	56%	-45%	-25%
Tropical	**Rooftop PV CH4 CHP Genset H_2 solution**	91%	87%	85%	-98%	-26%

Table 2: Summary results for 2030 scenario and 4 climate conditions.

nents and interfaces. It uses NATO Interoperability Standards and Profiles (NISP) [4] and Federated Mission Networking (FMN) [5] to build a new solution while respecting a certain degree of freedom for manufacturers and offering specific services for the exchange of energy data.

Cyber risk assessment methodology was applied to an electric microgrid to evaluate cyber threats and areas of greatest risk to define countermeasures and guidelines for maintaining the operation of an EEMC. The cyber risk analysis conducted using the MAGERIT [6] methodology reveals several critical areas within the environment that require attention to mitigate high risks. The findings emphasise the importance of strengthening security protocols, enhancing system monitoring, ensuring regular maintenance, and developing robust disaster preparedness plans. In conclusion, the risk analysis highlights the need for a proactive approach to risk management, focusing on high-risk areas. By implementing appropriate measures, safety can be significantly improved, ensuring continuity of operations and energy supply.

INDY has reviewed the procurement process for EEMC components and proposes the following measures:

- **Measure 1:** Use Directive 2009/81 to increase security of supply guarantee in conjunction with joint procurement.

- **Measure 2:** Technologies and products under INDY projects must be developed for both civil and military purposes.

- **Measure 3:** Develop a catalogue of "energy of the future for deployable military camps" products with an eco-label (certified Green Defence).

- **Measure 4:** Build up stocks of energy supply related materials. This would contribute to: providing better protection against the risks of security of supply and shortages of raw materials (including in the event of major tensions over demand, as we are seeing today in the case of ammunitions); and to the activity of a European Military Sales Mechanism as provided for in Article 14 of the European Commission's proposal of regulation creating the European Defence Investment Programme.

- **Measure 5:** Joint Procurement of EEMC would need to be done through the application of the Defence procurement Directive 2009/81. In this case, the best approach is to limit the role of procurement agent to EU Members, EEA Members, and the European Defence Agency. To address this, it would be recommended to delegate this procurement to EU organisations, either the European Defence Agency or the European Commission.

ROADMAPS FOR 2030 AND 2050

Based on the scenarios developed and through rigorous analysis, INDY experts identified 13 Key Energy Capabilities (KECs) which will provide improved operational performance when deployed in military camps. A Key Energy Capability refers to the application of scientific knowledge for military purposes and includes the development and use of advanced tools, equipment, and techniques to enhance military effectiveness and operational capacities. An energy solution is the integrated assembly of KECs, both hardware and software, designed to perform a specific function or set of functions within the military context. Operational performance refers to the availability of an energy technology or system to perform specific actions to achieve specific effects in a specific military operating environment. The KECs span energy production, storage, and conversion; transportation and nomad applications; mobility, energy management; and safety.

The final graphical roadmap, derived from the study and INDY expert opinions, is available in Figure 5-6. Each KEC represents a group of solutions, in which some of the solutions require longer periods to reach military specifications. Particularly relevant subjects or capabilities are outlined with separate lines of efforts. Progressive developments and capability enhancements are expected to bring KECs to the next generations. While some KECs will be available in the near future, others are expected to require longer periods and further steps before implementation is possible. The roadmap aims to outline the lines of effort that are necessary to transfer civil solutions to military grade and to improve existing military grade solutions leading to advanced military grade solutions.

The KECs are classified in 3 categories: those which can be taken off-the-shelf from the civil market, those which should be adapted to military specifications and those that need to be specifically developed for military applications. The status marks of KECs on the roadmap refer to following definition:

- Civ. Spec (Civil Specifications): Line of effort or KEC is available for the civil market (high civilian TRL 8-9, military TRL 5-6)
- Mil. Spec (Military Specifications): Line of effort or KEC is expected to be (widely) available in military grade. Achieving this step is either possible through hardening of civil systems or if the solution is already intended for military use (high military TRL 8-9)
- Gen II: Line of effort or KEC is expected to reach an improved version. Advanced military grade solutions expected to be available (high military TRL 9)

CONCLUSIONS

The INDY project is one of the first strategic European projects tackling green energy in the defence and security sector, strengthening collaboration between civil and defence partners to develop dual-use solutions for deployable military camps. INDY has developed a strategic roadmap towards energy independent and efficient deployable military camps based on a paradigm shift for energy production, conversion, storage, transport, distribution, and final usage.

The objectives are to reduce fossil fuel consumption, to improve energy efficiency, and to increase energy autonomy, all while guaranteeing the safety and security of operations. The solutions must be interoperable and deployable in different geographic and climate conditions, and for any camp size.

The key INDY outcomes are:

- Created functional requirements and scenarios for four camp types (suited for different climates and camp sizes) in 2030 and 2050
- Provided a database and detailed evaluations of emerging technologies for energy independence and resilience (technical, economic, and operational)
- Identified the Key Energy Capabilities (KEC) necessary for demonstrators
- Assessed risk involved in the deployment of advanced energy technologies
- Analysed procurement standards and procedures

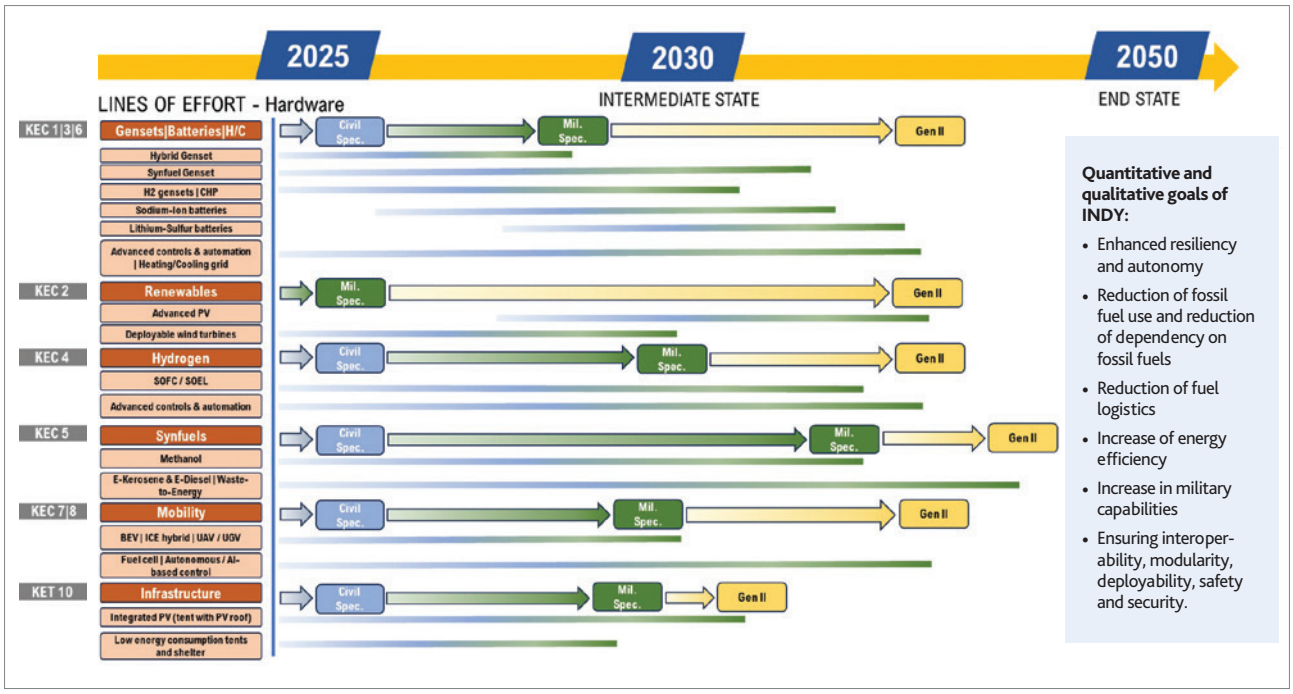

Figure 5: INDY roadmap for technology

- Created a proof of concept for a software tool for energy planning in military camps
- Blueprinted an energy infrastructure for 2030 which, compared to the 2020 infrastructure, would deliver the following improvements:
  - 35%–55% energy autonomy for camps
  - 35%–45% reduction in logistics burden
  - 15%–28% reduction in ownership costs
  - 40%–80% reduction in carbon footprint

It is expected that in 2030, legacy solutions using diesel powered generators will remain the primary electricity production system for military camps. Progressive introduction of PV and battery electrical storage will improve energy efficiency and reduce fuel importation. Military grade hydrogen solutions (H_2 storage, fuel cells...) will start being available. Microgrid solutions with advanced control will first be deployed for the smaller camps.

In 2050, all the Key Energy Capabilities will be available at military grade and the next generation will have been developed and qualified. Military camps will have a net-zero CO_2 footprint with high local electricity production (over 50%) and fossil fuel will be substituted by sustainable fuels (e-fuels, bio-fuels, hydrogen derived fuels...). Microgrid will be the standard solutions. Advanced control and management systems will be deployed using Artificial Intelligence solutions.

INDY project represents just the initial stage, laying the groundwork for future development and demonstration activities, including:

- Defining and applying standards for connection and communication.
- Assessing the performance of energy technologies in representative environments.
- Integrating solutions at the system level and qualifying them in real military settings.
- Demonstrating interoperability, cyber-protection, and resilience.
- Preparing joint acquisition programs at the EU level.
- Transferring solutions to armed forces.

With the support of the European Defence Fund and the active involvement of Ministry of Defence representatives in the INDY End-User Advisory Board, significant progress has been made in energy-efficient military camps. This progress paves the way for their effective deployment across the EU and associated countries' armed forces.

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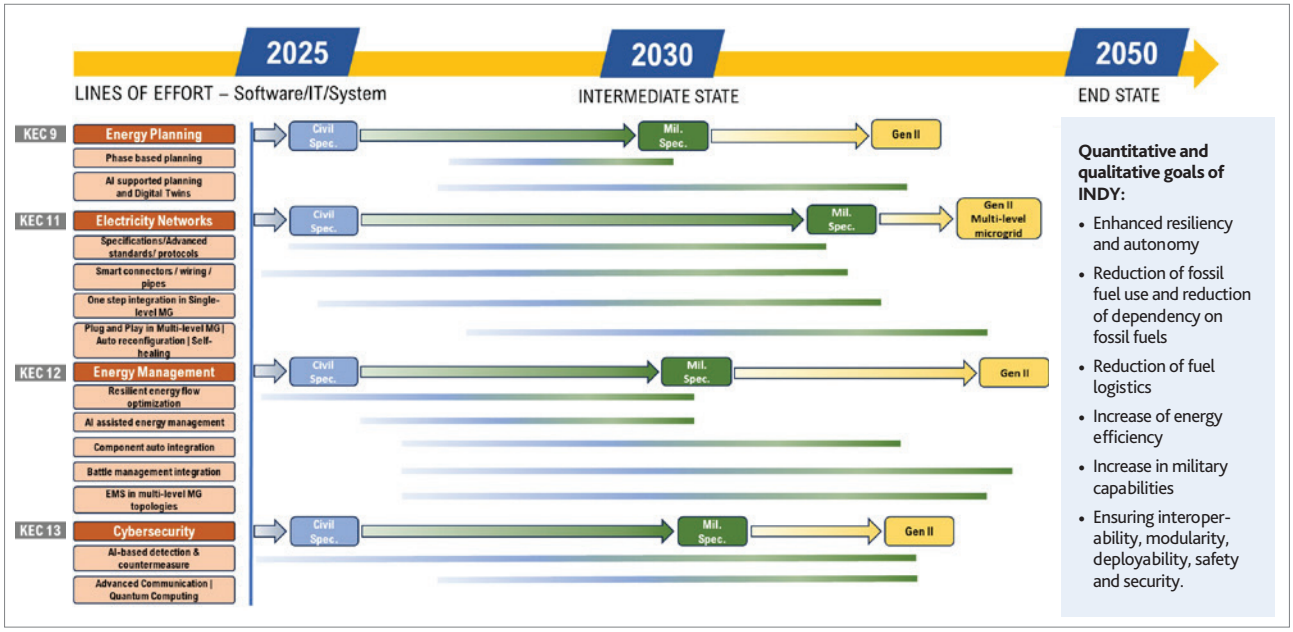

Figure 6: INDY roadmap for digital solutions

Highly Decentralized and Intelligent Power Systems – Risks and Opportunities for Energy Security

By **Enrique Kremers**

The energy sector has undergone significant transformation since the 1990s, driven by the pursuit of sustainability and emissions reduction under the context of climate change concerns. This shift involves transitioning from centralized, hierarchical structures to more **decentralized**, **meshed energy systems**, characterized by localized electricity production and consumption, as well as bidirectional flow capabilities.

From an energy market perspective, substantial deregulation has exposed various segments of the electricity value chain to competition, contrasting with the previous monopoly-dominated landscape. Notably, network operators remain natural monopolies due to infrastructure requirements. Digitalization has also improved grid management efficiency through advanced monitoring and real-time communication, focusing on integrating medium and low-voltage distribution networks via smart grid solutions.

While often associated with novel Distributed Energy Resources (DER) like renewable-powered plants and emerging technologies, decentralized energy systems are not entirely new; early electrification initiatives in the 19th century began with local, isolated grids that eventually expanded into interconnected networks for increased stability and economies of scale. Since the 20th century, large interconnected continental networks emerged, forming the largest ever human engineered systems: the NATO eastern flank, since February 2025 including the Baltics, is electrically interconnected with most western countries such as Portugal, at synchronized grid frequency and sharing common generation, as well as economic coupling through common markets. However, with increasing integration of variable renewable sources, balancing production and demand remains crucial for maintaining a stable grid frequency.

A hierarchically structured power system was highly efficient when demand was static and most of the production was controllable. That system was driven by the simple idea of flexible production following well predictable demand. Production and demand need to be always in balance to ensure a stable grid frequency of commonly

By **Enrique Kremers**

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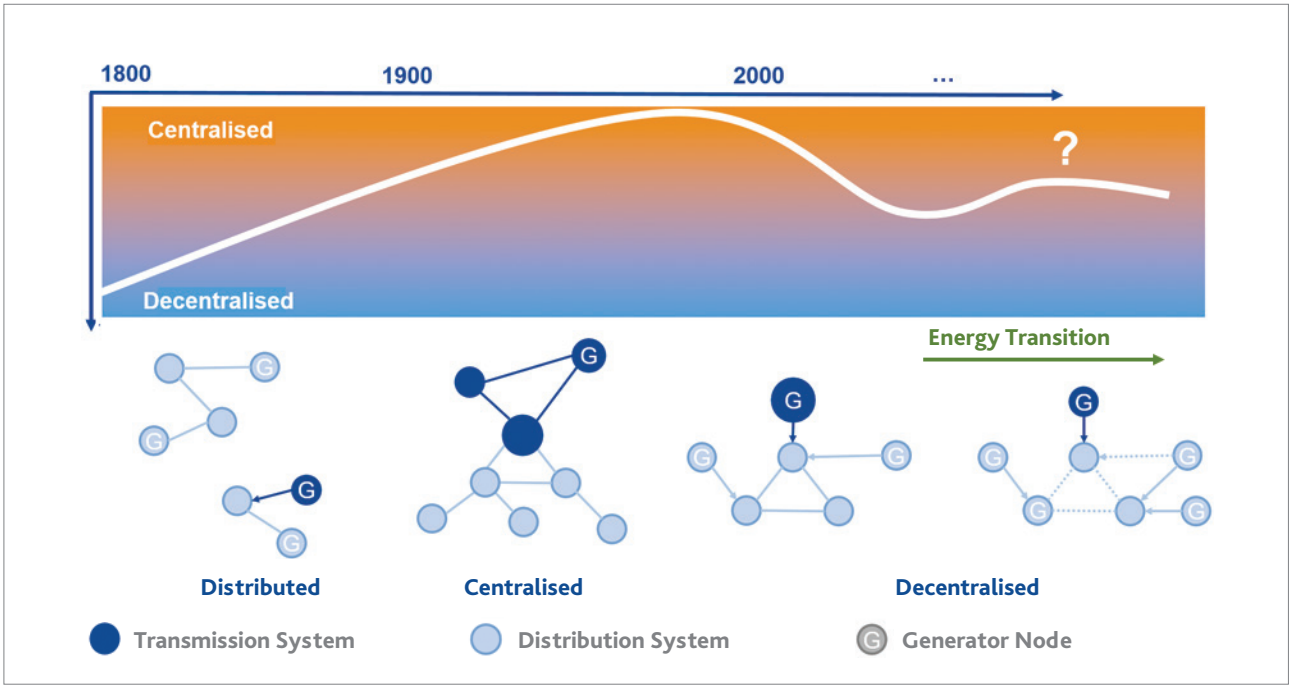

Figure 1: Centralization and Decentralization evolution in the energy sector

50 Hz in Europe. When production is larger than demand, frequency increases denoting an excess of instantaneous power in the system ("generators turn faster as no sufficient load is available to extract energy from the system"), whereas at the inverse, frequency will drop and denote a lack of supply.

With the introduction of larger shares of intermittent production which is mainly caused by solar and wind (see share of renewable electricity production capacity in 2022 in NATO and other countries), conventional generation needs to be more flexible to accommodate fluctuations that are less predictable. Additional flexibilization of the system to accommodate larger shares of renewable includes the introduction of Battery Energy Storage Systems (BESS) and the flexibilization of demand, shifting consumption to times where production is higher and vice-versa.

Electricity systems are transitioning from star-formed to meshed structures. Decentralization is a major trend. While not being a fully new concept, the decentralization process involving higher power fluctuations when integrating very large renewable shares is posing new challenges in terms of energy stability and security, as the structure and vulnerability surfaces of the system are also evolving.

ELECTRIFICATION: A GAME CHANGER AND A NEW DEPENDENCY

Whereas energy supply for large mobile military equipment, such as jet fuel or heavy-duty combustion engines will not be replaced by electricity as energy carrier in the near future, the trend of electrification in a number of sectors starts to have an undeniable impact on current and upcoming military systems.

The transition from Internal Combustion Engines (ICEs) to alternative powertrains in the civilian transportation sector is gaining momentum worldwide. Notably, some nations – including China – are 'leapfrogging' traditional fossil fuel-based vehicle adoption phases altogether, instead rapidly scaling up electric and low-carbon mobility solutions as they develop their national transport infrastructure. Electrical mobility is already having an impact on military fleets such as the United States Navy's shore-based vehicles, the British Army's base support vehicles, and various Special Operations Forces' (SOF) mobility assets, where reduced acoustic signatures, lower operational costs, and simplified logistics have made electrical mobility an attractive option for specific mission profiles. However, electrified mobility means new dependencies on charging stations and critical infrastructure components, such as high-power electrical grids, battery storage facilities, potentially introducing novel vulnerabilities and logistical complexities into military operations.

New equipment such as radar and communication systems, directed energy weapons, active protection systems, and unmanned aerial vehicles (UAVs), all contribute to an increasing demand for electrical power across modern militaries. Moreover, Cybersecurity and Network Centric Warfare with enhanced focus on AI-driven deci-

sion-making, IoT device integration, and real-time threat assessment will escalate computing workloads and thus electricity consumption significantly.

The historical focus of energy security on oil and gas as primary energy supply carriers is continuously shifting importance towards a predominantly electrified world, affecting also main military areas. Electricity becomes a highly critical carrier, that needs to be available for critical missions at the right place, right time and in sufficient amounts to ensure success.

FLEXIBLE INTELLIGENT ENERGY SYSTEMS: THE ROLE OF SMALL, DISTRIBUTED DEVICES

In Germany, solar photovoltaic (PV) reached a capacity of 100GW starting 2025 and is intended to more than double in 2030 (215 GW) according to the governmental roadmap [2].

As an example, while demand of electrical energy is predicted to only double (from 616 to 1300 TWh in 2045), the roadmap plans to increase its total installed electricity generation capacity from 210 GW in 2020 to around 850 GW in 2045 which is approximately a factor 4 in Germany. This oversizing is mainly required due to fluctuating renewable sources in combination with complementary dispatchable generation. Currently gas turbines will act as replacement after coal phase-out and as additional backup, to cover the so-called Dunkelflauten, when almost no wind or sun are available. Also, the less well-known Hellbrisen (high amounts of solar and wind injection, leading to overproduction) may destabilize the system. Intermittent production at large scale may lead to high power ramps, especially when large amounts of sun and wind enter or exit the system in a short time. Incentives for curtailing solar power have been introduced since March 2025 with the new Solar peak law.

When transitioning towards systems with very high shares of PV and wind power, besides additional flexible generation, storage is being rolled out, predicting an increase by factor 10 in Germany by 2045 [3]. Furthermore, sector coupling is providing means to shift energy peaks and valleys to other energy vectors, such as: with the mobility sector via bidirectional battery loading; with the heat sector (shifting large amounts of energy in the form of heat leveraged by technologies such as heat pumps and CHP); and with hydrogen systems. Whereas sector coupling delegates flexibility to other domains, failures may also propagate more prominently across different systems.

Renewable Share of Electrical Generation Capacity in 2022

NATO member states			
Norway	98%	Estonia	45%
Albania	96%	France	44%
Iceland	96%	Slovenia	44%
Montenegro	79%	North Macedonia	43%
Sweden	77%	Bulgaria	42%
Portugal	76%	Lithuania	41%
Croatia	72%	Hungary	41%
Canada	70%	Poland	40%
Denmark	69%	Slovakia	33%
Latvia	64%	United States	30%
Finland	61%	Luxembourg	29%
Spain	60%	Czechia	22%
Romania	60%		
Germany	60%	**OTHERS**	
Greece	57%	Europe	54%
Netherlands	54%	China	45%
Türkiye	54%	World	40%
United Kingdom	50%	Asia	40%
Italy	49%	Ukraine	25%
Belgium	49%	Russian Federation	21%

Figure 2: Share of installed renewable generation capacity in NATO and other countries. Source: [1]

At local scale, flexibility of small shiftable loads is an emerging trend. Many household appliances can adjust their energy use, and with intelligent energy management strategies, both large consumers like EV charging points and continuously operating devices like refrigerators can optimize their consumption automatically. This helps stabilize the grid by shifting power use to more convenient times without requiring user intervention.

Small distributed electrical equipment and energy storage will have a more active role in the future energy system, by participating in energy markets and contributing to system stability by providing large amounts of flexible power comparable to those of conventional power plants.

DIGITALIZATION: FLEXIBILITY ENABLER VS. NEW ATTACK SURFACE

Flexible device operation aligned with grid and market requires increased information flow. Distributed devices must identify optimal load shifts, congestion relief, or economic incentives. This demands smart, communicative Operational Technology (OT) devices capable of responding to network operator or market signals. This affects mostly larger power devices such as inverters, charging points and heat pumps. Energy Management Systems become a key component as they may interconnect all these devices, offering the possibility to control several of them. Today, one in ten German households already have smart energy management systems [4].

On the other hand, low-power devices such as consumer electronics and white goods are increasingly digitized, with most vendors offering internet-connected apps. Initially for passive monitoring, these apps now often enable remote control, such as turning on a washing machine via smartphone. In 2040, 11 billion of devices are expected to be connected to the internet worldwide with an aggregate flexibility potential of 185GW according to the International Energy Agency [5]. We can differentiate between:

1) Smart devices that are related to energy management systems connected to grid operator infrastructure control or other incentives mechanisms. They either communicate via secure channels (Smart Meter Gateways, Grid Operator Owned Communication Networks) or via vendor clouds or open channels over the internet; or both.

2) Small consumer devices that are not critical to the system and not connected to any secured communication channel related to the power system, but only to vendor clouds.

Especially the second type of devices are not secured in a special form as they are not considered part of critical infrastructure currently [6].

Whereas the energy sector needs digitalization for an efficient and secure integration of distributed generation, electromobility and emerging market players, a major threat potential due to new attack surfaces for cyber criminals and dependencies between the electricity and ICT systems, as highlighted by the acatech study, Energy Systems of the Future. [7]. Grid operators must actively combat these risks. Smaller, new players have increased influence on the security of the electricity supply, which means new responsibilities for regulatory implementation of protection measures. Political anticipation is required: consistent monitoring and adaption of the resilience strategy.

The current trends of decentralization and digitalisation poses a contradictory outcome: whereas the dispersion of energy sources and their increased redundancy may increase resilience, vulnerabilities emerge in a structurally transitioning system with increased fluctuations and new cyber-vulnerabilities.

LARGE SCALE DECENTRALIZATION: FOUR EXAMPLES

While decentralization is often cited as a resilience-enhancing strategy (exemplified by Ukraine's deployment of PV to increase attack costs by downsizing and spatial distribution), in the following we will present several empirical cases exemplifying the potential risks associated with highly decentralized and communicative energy systems (smart grids). These cases show how questionable design choices in the past have led to vulnerable or even unstable situations for the electricity system. We also project into one future case that potentially could arise within the ongoing decentralization process in a few years.

EARLY INTEGRATION OF DISTRIBUTED GENERATION CHALLENGES: THE EUROPEAN BLACKOUT-RESYNCHRONIZATION (2006)

In November 2006, a cascading failure originating from a single high-voltage line precipitated one of the continent's most extensive blackouts. The event resulted in a system split, where the power grid fragmented into isolated sections operating separately and causing widespread blackouts affecting millions of households due to automatic load shedding to prevent further damage to the system. The complex process of restoring a synchronized grid operation was disturbed by the unregulated reconnection of at that moment quite newly installed Distributed Generation (DG) units to the grid.

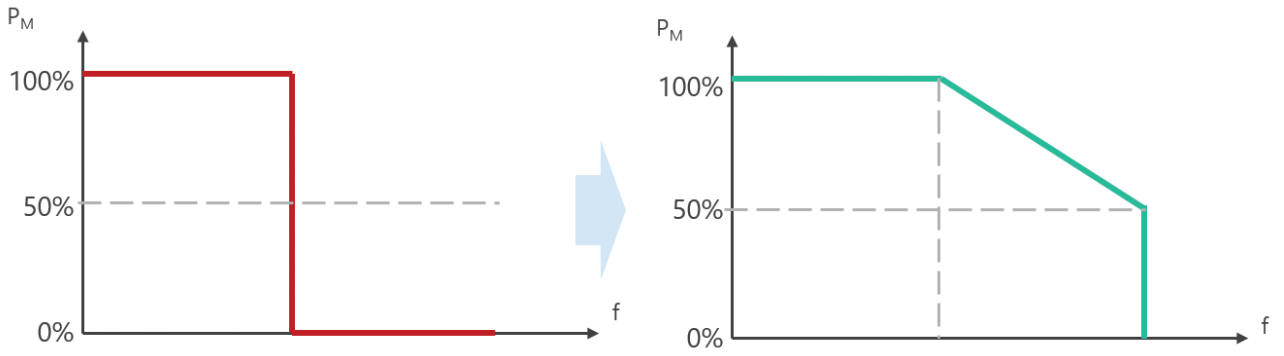

Figure 3: Frequency response of output power modulation (PM) of solar inverters before (left) and after (right) the retrofitting due to the 50.2 Hz issue

Notably, numerous small Combined Heat and Power (CHP) units, lacking coordination with centralized grid management, automatically reconnected to the grid without oversight. This uncoordinated resurgence of decentralized power sources threatened to destabilize fragile recovery efforts. Two shortcomings contributed to this critical situation: Firstly, the absence of real-time Monitoring of DG left operators blind to the dynamics at play. Secondly, the lack of centralized control mechanisms hindered the implementation of a unified restoration strategy.

Today, DG units are better secured to mitigate such risks, ensuring more reliable and coordinated responses to large-scale grid disturbances. This has significantly enhanced the overall robustness of Europe's energy ecosystem, informing better practices for the seamless integration of distributed power generation.

This large, first blackout during the up-ramping energy transition, served as an eye opener exposing the need for well-designed integration of distributed generation within the broader power grid, especially during emergencies. In consequence, concerted efforts were made to bolster the resilience of decentralized energy sources against similar incidents.

DESIGN FAILURES IN SCALING DISTRIBUTED SYSTEMS: THE 50.2 HZ PROBLEM (2011)

In the early stages of the German energy transition decentralized PV systems became a cornerstone of the renewable energy strategy. Between 2005 and 2011, the country witnessed an exponential increase in PV installations from 2.1 to 25 GW of peak capacity. However, this unprecedented growth also exposed a critical vulnerability in the system.

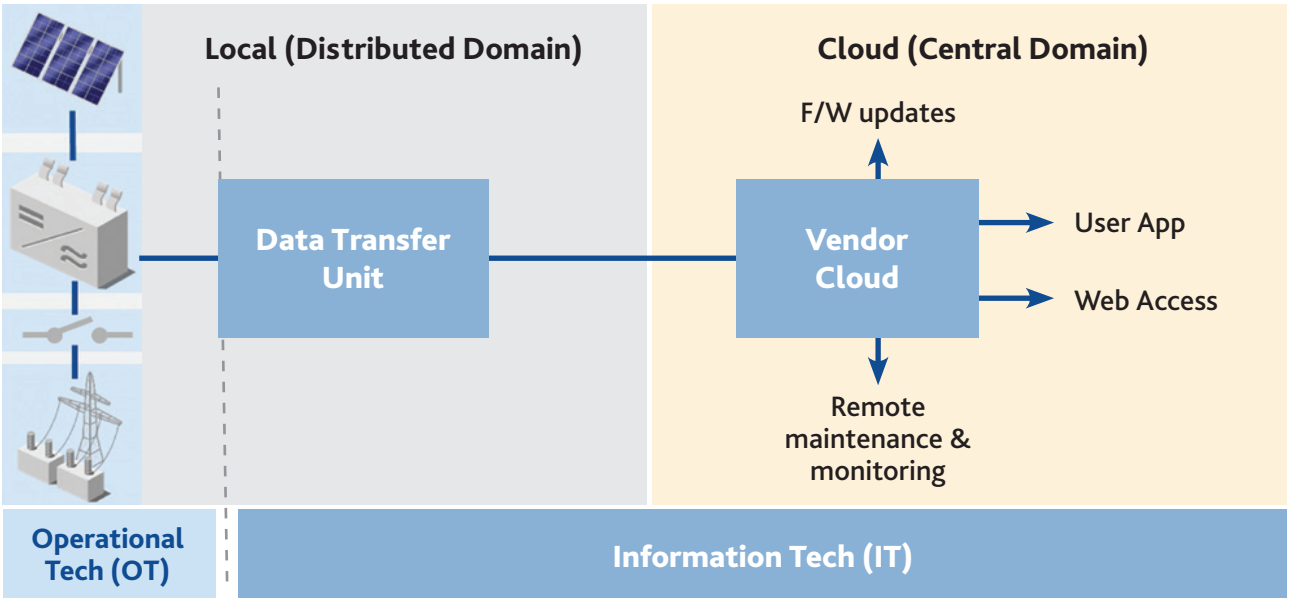

Figure 4: Local/Distributed and Central Cloud domains vs. Operational and Information Technology parts of the energy system. Adapted from [8].

The core of the issue was a well-intentioned yet overly simplistic protection rule: PV inverters were programmed to disconnect from the grid whenever the frequency exceeded 50.2 Hz, aiming to prevent overgeneration and thus contributing to stable grid frequency. While this safeguard may have seemed sufficient when having only small amount of PV installed power being irrelevant to overall system stability, it proved to be potentially stability-harming when the PV capacity scaled. On sunny days, when numerous PV systems simultaneously reached peak production, an abrupt, synchronized shutdown would instantaneously have drained up to 9 GW of power from the grid, an amount more than sufficient to destabilize interconnected European electricity network.

The urgency was recognized then by regulators and industry stakeholders. By 2012, a comprehensive solution had been implemented: a nationwide retrofit of existing PV infrastructure, replacing the abrupt on/off shutdown with a smoothened, linear gradual throttling mechanism. This upgrade, mandated by the System Stability Ordinance (SysStabV), enabled a far more nuanced response to fluctuating energy demands, effectively mitigating the risk of large power steps. In 2025, with 100 GW of PV capacity seamlessly integrated into the national grid, the once-troublesome 50.2 Hz threshold serves as a reminder for effective design practices of distributed protection systems.

Scalability is often underestimated in disrupting systems, especially of decentral nature. Possible evolution paths for a scaling system should be considered from the beginning. Supportive studies using simulation and extrapolation models can assess future impacts.

CYBERTECHNOLOGICAL VULNERABILITIES OF DISTRIBUTED GENERATION: SOLAR INVERTERS (2023-2025)

Within the deployment of solar energy, small, self-installable so-called "balcony photovoltaic" systems are penetrating the energy system quickly due to simple installation, economic effectiveness and low administrative burdens. With approximately 866,000 plug-in micro-inverters installed in Germany in 2025, with capacities of 600-800W per device and thus a total generation power of around 700 MW pose already significant amounts of power. This is comparable to a typical conventional power plant. A significant majority of these devices are cloud-connected, ostensibly enhancing user experience and monitoring capabilities.

In 2023 vulnerabilities within small micro-inverter vendor's products were found, compromising the security and reliability of these smart devices [8]. Leveraging unpatched exploits, cybersecurity experts showed how it would have been possible to command clusters of micro-inverters, orchestrating and synchronizing their actions to amplify the effects. Due to the absence of any kind of encryption for the firmware update process, unauthorized access via merely knowing the device's serial number was possible. Moreover, even basic accounts enjoyed unfettered privileges to push updates to numerous devices through the cloud server. The capability to remotely trigger grid relay toggles at exactly the same moment, utilizing NTP (Network Time Protocol) time to enlarge impact by creating an aggregating effect leading to very quick and large power variations.

Cyberphysical threats, the destruction of hardware via

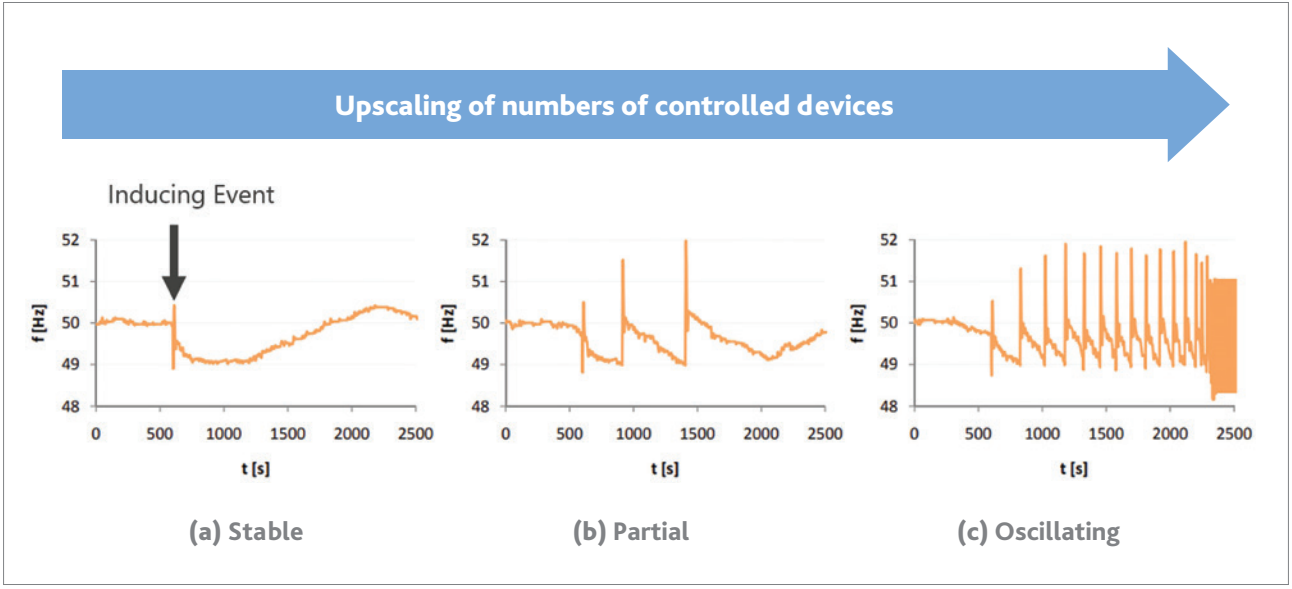

Figure 5: Oscillations effects that emerge when upscaling large number of small controllable devices that react to frequency drops

cyber-attacks, firstly gained wide attention after the 2010 Stuxnet hijack of Iranian nuclear centrifuges. The software caused physical damage while deceptively showing normal operation to system monitors, delaying detection and increasing damage.

Manipulating the Pulse Width Modulation (PWM) signals controlling MOSFET Transistors within the PV inverters could induce overheating leading to device destruction. Besides posing tangible safety risks to the local installation, the destruction of large numbers of inverters would mean massive economic damage, with subsequent delays in replacement of substantial amounts of generating power.

Besides physical damage due to malicious manipulation, in November 2024 large numbers of several inverters in USA, UK and Pakistan were deactivated remotely by a Chinese vendor due to juridical disputes. In 2025, the European solar industry reviewed the general cybersecurity of inverters [9], identifying several risks due to possible remote control of a massive number of devices, with an installed power of 200 GW Europe-wide. Shortly after, the US Department of Defense reported rogue chips to be found in several inverters, allowing for undocumented communication [10], whereas further destabilization risks via targeted orchestration have been identified [11].

Power inverters, present in any PV installation, can pose serious risks to grid stability already today. Small but massively deployed, communicating energy devices are part of critical infrastructure and can compromise the grid in the same way as large power plants. Vendors and responsible parties need to comply with new, adapted security regulations for distributed power devices urgently.

UNINTENDED CONSEQUENCES OF MASSIVELY INTERCONNECTED SYSTEMS ON GRID STABILITY: SWARMING EFFECTS (2045)

Inverters and larger power consumers - such as EV charging stations and heat pumps - will likely fall under critical infrastructure regulations in the medium term, including the EU Cyber Resilience Act and the Network and Information Security Directive (NIS2). However, virtually any connected device can, in the aggregate, contribute critical power volumes, as the following future-projected scenario shows.

Small but highly present devices offer interesting, aggregated potentials and may provide future ancillary system services such as frequency or voltage stabilization. Even though individual power of cooling appliances, such as fridges and freezers, rating is below 100W per unit for modern devices, 110 million of these devices across Germany alone, collectively represent a gross installed capacity of 8.8 GW, operating 24/7. In aggregation they offer a net power flexibility of +/- 2.4 GW, positioning these devices as viable contributors to frequency-driven stabilization efforts, including exemplary applications such as frequency support schemes, in which devices are temporarily disconnected when the grid is overloaded to support the balancing or load shedding mechanisms.

Simulations incorporating such decentralized control mechanisms designed to harness the collective potential for grid stabilization showed unexpected effects: the deployment of such strategies inadvertently can give rise to unwanted emergent behavior, notably synchronization effects among the dispersed appliance population. This swarming phenomenon, where individual device responses become synchronized in unintended ways, can lead to cascading effects when upscaling the number of controlled devices [12]. Such oscillations can lead to similar outcomes as in the recent Iberian Peninsula blackout of 28.04.2025. This poses new risks in possibly underestimated under-the-radar devices, underscoring the need for systemic designed control architectures capable of mitigating counterproductive self-organization of large number of devices. Such effects could even be exploited by malicious actors by inducing such a cascade intentionally.

In some years, even very small sized, interconnected consumers such as white goods could play a substantial role in power grid balancing. If not properly designed, these mechanisms can lead to either self- or intentionally induced synchronous oscillations leading to dangerous grid collapses.

DECENTRALIZATION IN THE INFORMATION AND COMMUNICATION LAYERS

Besides physical distribution of assets, decentralization of information, data and control is taking an important role in the energy transition, as it evolves from few large to many small controllable nodes. Energy Management Systems (EMS) allow monitoring, controlling, and optimizing power usage for complex energy systems. They can operate at different scales, from individual buildings to extensive power grids. Leveraging advanced technologies like IoT, AI, and data analytics, EMS enable efficient energy usage & distribution, enhance stability and promote sustainability.

Energy management systems can have different structural approaches of rather centralized or decentralized nature. When managing a large number of energy devices, the choice between centralized and decentralized control techniques depends on priorities regarding system resilience, decision-making autonomy, and maintenance simplicity. While centralized control offers streamlined operations, decentralized approaches provide enhanced robustness and adaptability, though

often with added complexity. Ultimately, a hybrid model balancing aspects of both paradigms might offer the optimal solution for many energy management scenarios.

Decentralized control schemes include price incentivized signals, such as Time-of-Use tariffs, offering different prices on fixed time windows, or dynamic tariffs. Also, other incentive signals not directly related to price, such as physical signals providing physical state of the grid, such as grid frequency or voltage, can be used to enable autonomous distributed control [13].

Grid architectures that rely on cellular approaches are most promising in this regard, offering resilient structures inspired from natural systems that show improved scalability and extension capabilities [14], [15]. These architectures can be built by interconnecting different microgrids, that form autonomous grid cells which can work either independently or in a collaborative form. Especially in the military application field, islanding capabilities and modularity of electric networks will become more important in a context with higher amounts of electrified mobility and weapon systems, such as rechargeable UAVs. Decentralized control approaches also shall allow partial operations even if the overall system is degraded or communication fails.

Just as combat clouds distribute decision-making and resources across a network for enhanced agility and resilience in dynamic environments, decentralized energy management disperses generation and control throughout the grid. Both paradigms prioritize on-the-edge intelligence and local response to optimize performance, moving away from vulnerable, single point of failure architectures to achieve greater robustness and adaptability when facing disruptions.

To manage complexity efficiently, a design-driven approach, inspired in principles from naturally resilient systems by developing organic, cellular grid architectures is proposed. These hybrid structures aim to integrate the benefits of traditional centralized and modern distributed systems, incorporating essential attributes such as:

- **Modularity:** Designing the grid as a collection of independent, interchangeable modules that can be easily replicated, scaled, or replaced.

- **Redundancies and Distribution:** Incorporating duplicate or supplementary components/systems to ensure uninterrupted service despite component failure or high demand spikes, ideally physically and logically distributed.

- **Interconnectedness:** Strategically linking modules and subsystems to facilitate efficient energy transfer, resource sharing, and holistic grid management, while minimizing communication to strictly necessary levels.

- **Edge Intelligence:** Empowering grid modules or individual entities to work with local information, on-the-edge intelligence, including failsafe fallback modes in case of communication breakdown.

- **Self-healing Mechanisms:** Implementing automated processes that rapidly detect, isolate, and recover from faults or partitioning (black-start recovery), potentially operating in isolation (islanding) until full restoration.

CONCLUSIONS

The energy transition involves an intrinsic decentralization process. This poses new challenges to security of critical infrastructure, but also opportunities:

Firstly, **awareness and sensibilization** on energy security among new actors entering the electrical system at lower grid voltage levels is essential. Even if smaller device manufacturers may seem irrelevant, they may be involved in system stability and security stakes in the near future. Remotely operable smart devices have to be considered a part of **Critical Energy Infrastructure** from regulatory point of view, as soon as a potential aggregation of them can have impact on stability.

Decentralized systems should be planned **scalable and resilient *by-design***. This includes local operation modes through autonomous, cloud independent, on the edge decision making and fallback solutions in case communication breaks down. Furthermore, critical devices such as inverters need to be grid-supporting allowing grid forming capabilities and black starts. Special attention needs to be put to vendor clouds, in order to avoid new central attack surfaces.

Resilience can be increased by **managing complexity** adequately. Whereas decentralized control may increase resilience on the operational layer, unwanted self-organization and malicious induction of cascading effects should be considered in early planning phases. **Simulation & Digital Twins** help to de-risk by anticipating upscaling effects and designing protection. With systemic design approaches, **Energy Management Systems** can make use of positive emergence, providing organic robustness inherently.

The energy transition is an important instrument towards climate change challenges. However, from a

military point of view it should be leveraged as a **catalyst for augmenting the resilience** of critical infrastructures within both civil and military sphere. The energy transition should be embraced not only in form of decentralization of physical assets, but meantime with an aligned, adequate level of **decentralization of control, data and decision making**, providing inherent strategic advantages in both physical and cyber domains, ultimately enhancing overall system resilience.

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Ocean Power Generating Technologies - A Vast Renewable Energy Potential

By **Jutta Lauf, Reiner Zimmermann, Wsewolod Rusow**

Electric power generation is taking an ever-growing share of the global energy consumption of industry, private households and even the military. Modern societies rely increasingly on stable and secure electric power supplies, with a trend to non-fossil, renewable energy sources.

This article explores the ocean's vastly untapped power production potential, the physical and chemical energy forms as well as the conversion principles and technologies used. Some ocean power generation technologies have already been exploited for decades and, in one case, centuries, with well-established technologies. Others are currently in developing states or exist as prototypes only.

This article explains relevant technical terms followed by a technical discussion of the most intuitive technologies which harness the potential and kinetic energy of the tides and waves. Then the vast thermal energy of tropical oceans for producing electricity will be discussed, as well as the technologies using spatial water salinity gradients.

CHARACTERISTICS OF NON-RENEWABLE AND RENEWABLE ELECTRICITY TECHNOLOGIES

For conventional power plants a constant fuel supply is crucial for their production capabilities. The supply and transport chains for non-renewable sources like fossil fuels and uranium are well established and technically mature. Fluctuations in production, market availability, transport and pricing are mainly due to geostrategic changes and political decisions. For conventional renewable energy sources for electric power production, a comparably reliable and continuous supply is only given for geothermal power plants as the conductive thermal heat is provided by the physical processes in the earth's core.

Power generation from renewable energy sources other than geothermal – like from solar radiation, movement of air masses (i.e. wind) or rivers (gravitational hydropower) - is volatile and not fully controllable. However, for ensuring a demand driven and reliable electric power production by renewable technologies, energy supply forecasts

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for short-term (days to weeks) and long-term (months to years) availability are crucial. Hourly forecasts for wind speed, solar radiation and precipitation are available for a few days only. Battery storage options of large amounts of electricity during periods of oversupply are extremely expensive and are currently not feasible. In contrast, long-term predictions for tides, sea temperatures and salinity concentrations – which drive ocean technologies described in this article - are available and reliable from a local to a global scale.

If the energy supply can only be forecasted in a short-term scenario (solar, wind, hydro) the power generation technology is termed un-predictable. If forecasts are available on a long-term basis, the technology is termed predictable. Long-term predictability of renewable power production is sometimes considered as good as for conventional power plants. This classification directly leads to the more commonly used concept of the controllability of a power plant. Controllability is given when a plant can make use of its full capacity within its respective reaction time. This is only possible, when sufficient energy for power generation is constantly available.

The limited predictability of wind speed and solar radiation in combination with lacking storage capacities render electricity production from wind turbines, photovoltaics (PV) or concentration solar power (CSP) an inflexible power source. In contrast, the power production from CSP plants with thermal energy storage (CSP-TES) or hydropower dams with pumped hydropower is a controllable and flexible energy source due to the inherent energy storage capacity lasting from hours to a few days. This allows the control of electric power production on demand (Table 1).(Lauf et al. 2021; Lauf and Zimmerman 2023)

In industrial regions outside of the global Sunbelt it is currently not possible to cover the high electricity demand with renewable energy sources, while within the global Sunbelt calculations by Benitez et al. 2021 (IRENA 2020) have shown that this task can be achieved by installing CSP-TES plants (Lauf et al. 2021). Outside the global Sunbelt the use of ocean power may contribute to establish fully renewable electricity supply systems. The potentials of electric power production from the oceans will be discussed in the following.

THE ELECTRIC POWER PRODUCTION POTENTIAL OF THE OCEANS

The current electric power production from saltwater resources, often called "ocean power", is very small with respect to the global electric power production. The current globally installed electricity production capacity across all ocean power technologies is relatively small and represents only about 0.5% of the worldwide installed electric capacity (Figure 1).

The energy content of the ocean is sourced by (a) the gravitational influence of the moon causing tidal movements, (b) wind action which injects potential and kinetic energy into the water, (c) radiation from the sun which increases the thermal energy content and (d) the influx of ions (salts) from freshwater systems which increases the chemical energy of the water. All these energy sources are large and predictable over time, though not always on longer timescales e.g. months. Thus, covering high electricity demands from renewable ocean energy sources appears to be possible. Tidal range or stream power is using (a), Wave power is using (b) and to a lesser extent (a), Ocean Thermal Energy Conversion is using (c), Salinity gradient power is using (d).

The global electric power production is still dominated by fossil fuels. Nuclear energy capacity is small, by definition non-renewable and may have limited future expansion potential due to environmental and supply concerns. Global renewable electric power capacity is currently dominated by solar, wind and hydropower technologies. Biomass energy contribution is small and faces limited expansion potential due to the food vs. fuel competition, amongst other reasons. Geothermal power generation

Table 1: Production characteristics of common renewable and carbon-free energy technologies relying on sun, wind, and freshwater resources.

Technology	Predictability of production	Storage capacity	Controlability	Flexibility
Wind	Short-term	No	No	No
Photovoltaic (PV)	Short-term	No	No	No
Concentrating Solar Power (CSP)	Short-term	No	No	No
Concentrating Solar Power with Thermal energy storage (CSP-TES)	Short-term	Thermal energy	Yes	Yes
Geothermal	Long-term	Thermal energy	Yes	Yes
Hydro dams	Long-term	Reservoir	Yes	Yes
Biogas/Biomass	Long-term	Fuel	Yes	Yes

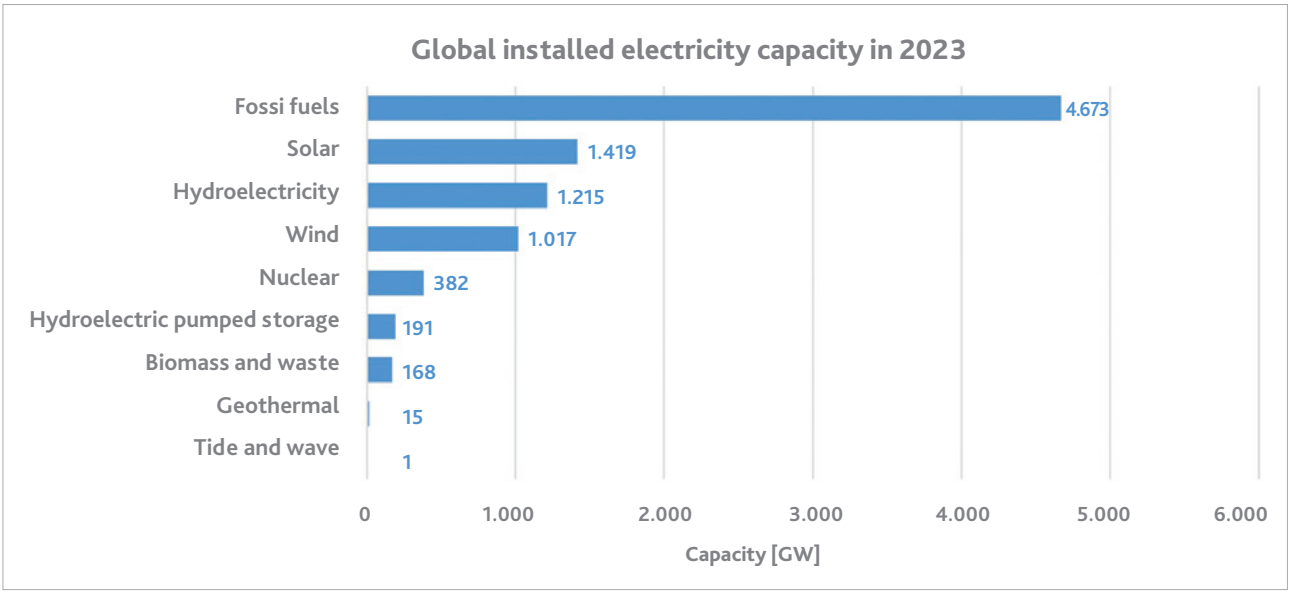

Figure 1: Worldwide installed electricity capacity [GW] in 2023 by energy source. Modified after Statista (2025). (Statista 2025)

capacity is marginal but has a regional untapped future potential (Figure 1).

Compared with all the technologies mentioned above, electric power generation from the oceans is still marginal with a total of 534.7MW (Figure 2 A). From this installed capacity almost all power plants use tidal range technologies (532.1MW).

The discussion of future ocean power production potential is dominated by Wave Energy, Ocean Thermal Energy Conversion (OTEC) and Salinity Gradient technologies (Figure 2 B). While being the oldest and most established technology, tidal range power generation is often neglected in the current discussion due to a lack of investment and technological development in the past decades, thus being deemed an outdated technology by investors.

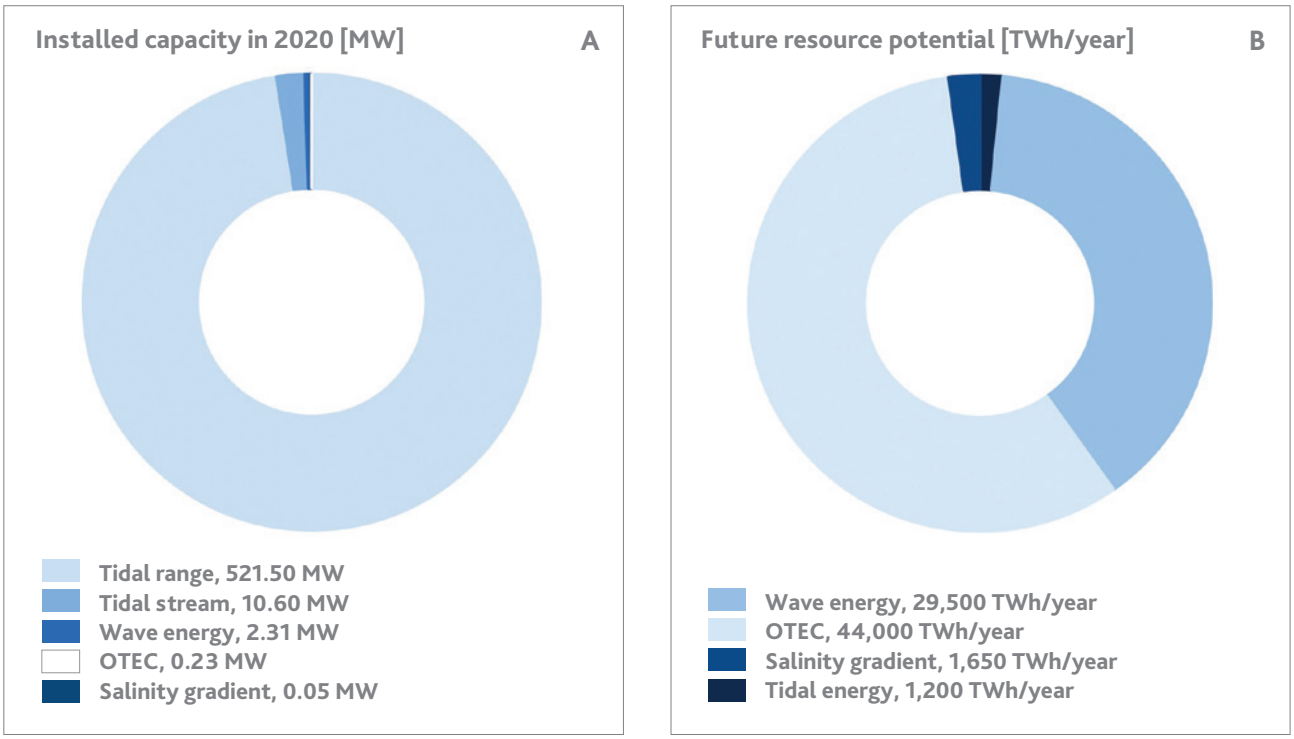

Figure 2: Actual and potential future share of ocean power technologies: (A) Installed capacity of ocean power technologies in 2020 and (B) projected future yearly global production potential. Tidal energy shown in (B) represents the sum of tidal range and tidal stream technologies.
Modified after International Renewable Energy Agency 2020. OTEC = Ocean Thermal Energy Conversion (IRENA 2020).

The technology with the highest future production potential is estimated on a conservative basis to be OTEC (44 000TWh yr^{-1}) followed by wave energy plants (25 500TWh yr^{-1}). The combined annual production potential for all ocean power technologies could also reduce the energy dependence of power technologies and is estimated to be between 45 000 and 130 000TWh of electricity, respectively. This would cover twice the current global demand.(IRENA 2020)

Given the huge energy potential and the fact that ocean power could be generated in most regions of the world where nations have access to coastal areas, NATO countries could reduce their current geostrategic dependence on fossil fuels as well as on future Sunbelt-generated renewable energy and increase independence of remote military bases. Ocean power partially eliminates regular and timely fossil fuels transportation needs, increases the energy security and resilience of remote military installations because of the exceptional load stability and predictability.

This article will review the main ocean power technologies and assess their potential for renewable and resilient electric power production. The review will start with presenting established and prototype technologies using tidal movement and wave power, explore the vast potential of ocean thermal energy and discuss electric power generation from salinity gradients.

TIDAL POWER

Tides are mainly caused by the moon's gravitational force but are also influenced by the sun. Their occurrence, strength and range is defined by astronomic constellations and topographic features and can be calculated many years in advance for every point of the global coastlines. This allows predictable energy production from tidal power plants. Tidal power plants can add a controllable electricity source to the global renewable power production mix. They are most effective at latitudes above 40° in both hemispheres because the Coriolis-force deflects water to higher latitudes.(Lewis et al. 2011)

Electricity generation in tidal power plants is performed by hydro-kinetic turbines which are using either the gravitational gradient of temporarily stored ocean water (tidal range power) or directly by immersion into the tidal flow of water (tidal stream power). They operate in harsh conditions, as sea water is corrosive and the kinetic power of the water is immense and sometimes destructive. Submerged turbines are also difficult to access for maintenance and repair work.(IRENA 2020)

TIDAL RANGE POWER

Tidal range power stations are preferably situated on coasts with a high tidal range and typically at rivers, estuaries, or inlets, which can easily be blocked by a dam. Rivers are preferable sites because the river influx adds to the storable quantity of water for power generation during low tide. They generally consist of an artificial water reservoir to store the water from the high tide, usually via a dam, a sluice to fill the water reservoir and another sluice to direct the water to the turbine which is often installed within the dam. The potential energy difference of water levels between the two sides of the dam drives water through a turbine and transforms it into rotary energy which in turn drives an electric generator. The higher the potential energy difference, the higher the amount of electricity produced.(Roberts et al. 2016; Lewis et al. 2011; Boretti 2020)

Tidal range powered plants are an old technology. The first known tidal mill for grinding grain was built in the 7th century by monks on Ireland's NE coast. (Charlier et al. 2004) The century long usage of tidal power demonstrate the simplicity and effectiveness of this technology.

Worldwide, only three tidal range power plants are currently operational, two of them have a capacity of >200MW: the Rance plant in France and the Shihwa Lake power station in South Korea. Both plants are discussed with their technical details and the associated social and environmental costs and benefits.

ELECTRICITY PRODUCTION AND SOCIAL CONNECTIVITY: THE RANCE TIDAL POWER STATION IN FRANCE

At the estuary of the river Rance in Brittany (France) several tidal water mills were in operation from medieval times onwards because of the favourable topographic conditions and the high tidal range of 8.2m on average. There, the French power company Électricité de France (EDF) inaugurated in 1966 the first modern tidal power plant (Figure 3C).

The dam of the Rance power plant is 700m long spanning the entire width of the mouth of the river Rance where it flows into the British Channel. It holds 24 reversible turbines with a combined capacity of 240MW. Its long-term annual power production is on average 500GWh which amounts to 0.12% of the annual energy consumption of France.

Electricity production in the Rance Tidal Power Station is versatile. During high tide (Figure 3A), the water level on the seaside is higher than on the river side, pushing water through the turbines at the bottom of the estuary. During low tide (Figure 3B) the water level in the river is higher, pushing water through the turbines to the ocean. Sluices can be closed at high tide and therefore the electricity production can be reduced, stopped or postponed. In practice, most of the power generation is done during low tide.

The estimated Levelized Cost of Electricity (LCOE) is 7.98 or 4.56 €-ct kWh^{-1} for an assumed service time of 25 or 50

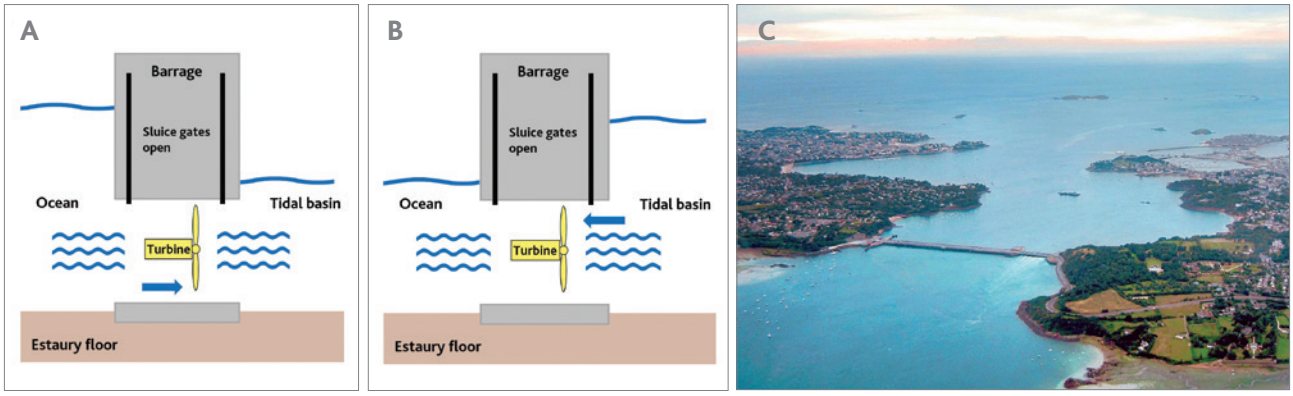

Figure 3: The Rance tidal power station. Configurations for electricity production during (A) High tide: Water from the ocean is pushing through the turbines into the river Rance. (B) Low tide: Water from the river Rance is pushing through the turbine into the sea. (C) Aerial photo of the Rance Tidal Power Station (Brittany, France). Visible in the background is the British Channel in the front the Rance river. Centre: Barrage (dam) with integrated turbines to generate electricity. The dam also serves as a road connection across the river.(EDF 2024)

years, respectively. The 50-year service time was reached in 2016. No official data from EDF are available and currently no plans for decommissioning the plant are known which will result in even lower LOCE in the future.(Boretti 2020; Statista 2020)

The effects of the dam on the region are various. Local residents valued the dam more for its integrated road rather than for the cheap power production. The shortcut over the dam considerably reduced the travelling time between communities on both sides of the bay while the power plant itself and the reservoir behind the dam became a tourist attraction.(Électricité de France 2025) The dam caused an increased silt deposition behind the barrage and the fish population in the Rance was affected by the local extinction of some native fish as well as the remigration of formerly locally extinct fish species into the Rance. (EDF 2024; Boretti 2020)

FRESH SEAWATER EXCHANGE AND ELECTRICITY SUPPLY: THE SHIHWA LAKE POWER STATION IN SOUTH KOREA

The Shihwa Lake Tidal Power Station in South Korea was built in 2011 and surpassed the Rance Tidal Power Plant with 254MW of installed capacity.

The Shihwa Lake is an artificial lake claimed from the ocean. Its construction was completed in 1994. A 12.7km long seawall created a 56.6km² lake and generated land gains of 33km² with three new cities and large industrial complexes. The Shihwa Lake was intended to become a freshwater lake fed by several small rivers and should provide water for agriculture. However, due to an imbalance of fresh and wastewater influx, it transformed into a highly polluted lake void of living organisms.(Park and T. S. Lee 2021; K-Water 2024)

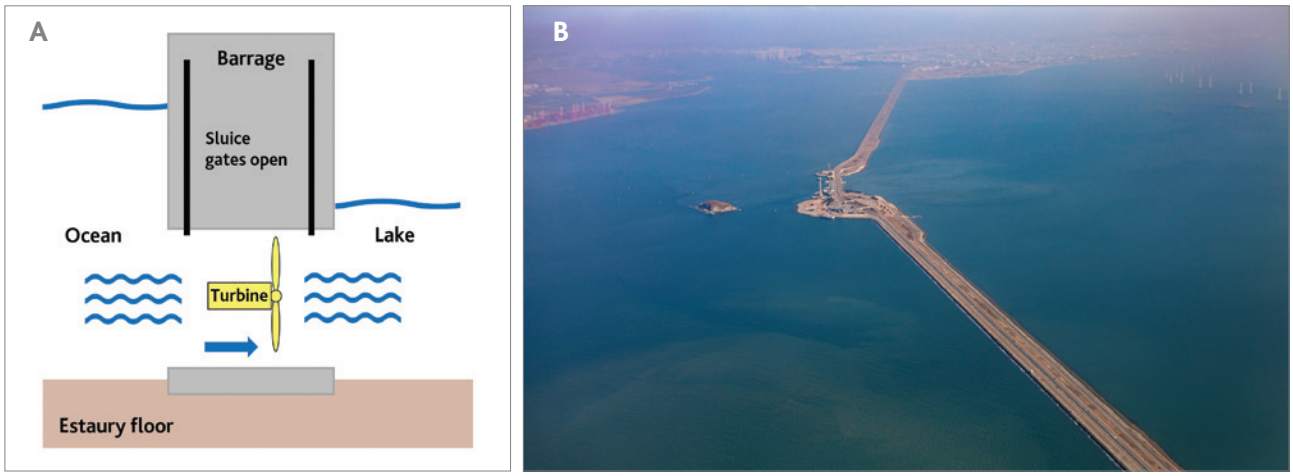

Figure 4: The Shihwa Lake tidal power plant. (A) High tide electricity production. (B) Aerial photo of the Shihwa Lake power station. Left is the ocean side; right is the lake side of the plant. In the centre of the dam the sluice gates and turbines are visible. Photo by Arne Müseler / arne-mueseler.com / CC-BY-SA-3.0 / https://creativecommons.org/licenses/by-sa/3.0/de/deed.de (Müseler 2020).

In 2000 the government begun a project to improve the water quality of the lake. The official status of the lake was changed from a freshwater to a saltwater body and a tidal power plant was planned to be integrated into the existing embankment with two objectives: To allow the exchange of water between the newly established saltwater lake and the ocean and to produce electricity. (Park and T. S. Lee 2021; K-Water 2024)

The Shihwa power plant was inaugurated in 2011 with the primary goal of improving the water quality in the lake. Since it was designed for electricity generation during high tide only when water flows into the lake (Figure 4A), it operates only twice per day for 4h and 25min each time. The sluices are closed before the flood tide, and when the sea level raises to approx. two meters above the lake level, the turbine gates are opened, allowing the turbines to produce electricity. When the ocean and the lake water level become balanced, the turbine gates close and the sluice gates are opened, allowing the lake water to flow to the sea. In this way approx. half of the total volume of the lake is exchanged twice per day, improving the water quality considerably. This "one-way-flow" tidal power generation mode results in a relatively low-capacity factor of 25%, but was chosen for environmental purposes of allowing efficient sediment and pollution drainage. (Park and T. S. Lee 2021; K-Water 2024)

Ten turbines with a capacity of 25.4MW each (total: 254MW) produced between 2011 and 2024 approx. 550GWh per year. The LCOE of the Shihwa plant is estimated to be as low as 2.28 to 4.56 €-ct kWh^{-1} depending on the assumed service life of 50 or 25 years respectively, but actual data are not yet available (Boretti 2020; Statista 2020).

The Shihwa tidal power plant is an excellent example of the versatile technology of tidal range electricity production as it solves two problems in one take: First the previously ecologically "dead" freshwater lake was transformed into an intact seawater ecosystem and second, electricity is produced from a renewable source in a predictable manner.

TIDAL STREAM POWER

A second possibility to use the energy of the tides is by transforming the kinetic energy of the water flow during the change of the tides. This technology does not dependent on specific coastal landforms. While using tidal stream power has no technological history, groundbreaking developments have been made over the past years.

Tidal stream plants are favourably situated on coasts with a high tidal gradient. Topography can enhance the induced tidal currents and narrow straits e.g. between islands or narrow inlets are a preferred location.(IRENA 2020; Lewis et al. 2011)

Tidal stream plants require the possibility to install turbines on the sea floor or submerged on floating scaffolds which are anchored. The tides rush water through the turbines and the kinetic energy of the current is transferred to the turbines which drive a power generator. The stronger the current, the higher the amount of electricity to be generated.(IRENA 2020; Lewis et al. 2011)

Tidal stream turbines are approaching a mature technology level and may become more prominent than tidal barrage plants. Several turbine technologies are under investigation such as horizontal- and vertical-axis turbines, oscillating hydrofoils, Archimedes spirals and tidal kites.

Horizontal-axis turbines and tidal kites have been preferred in recent years in developing projects. The turbine development started with 100kW capacity models and has now reached 1.5MW. Smaller turbines like tidal kites may have a market of their own for remote islands and isolated facilities while big stationary turbines could be the future for large-scale applications.

Tidal induced water flow can reach up to 5.5m s^{-1} (19.8km h^{-1}) but varies widely depending on the location. Wind turbines require at least 5m s^{-1} of wind speed to generate electricity, while the energy harvest of water turbines starts at much lower values because the energy harvest of a turbine is primarily determined by three factors: the flow speed of the medium, its density and the width of the turbine rotor. The density of water is approx. 1000 times higher than that of air, which means that compared with wind turbines, high electricity harvests from water turbines can be achieved at low water flow speeds and with short turbine wingspans.

A COMMERCIAL TIDAL STREAM PLANT: THE MEYGEN PLANT IN SCOTLAND (UK)

Since 2018 four 1.5 MW turbines are operational between the northernmost coast of Scotland and the uninhabited Stroma Island (Pentland Firth). Each 150-ton turbine has three blades with a rotor diameter of 18m. The turbines include a module which rotates the turbine at each slack tide to face into the subsequent low or high tide flow. They are mounted on a 1450-ton gravity foundation that supports the turbine with its own weight. The water flows with a speed of up to 18.5km h^{-1} (5.1m s^{-1}) which is among the highest flow speeds globally. Until the end of December 2023 61GWh electricity were generated. In the final state 398MW of capacity should be installed in several project phases. (SAE Renewables 2024; Tethys 2025a)

The generated tidal stream electricity can easily be fed into the national grid because the existing grid infrastructure from the now decommissioned nuclear plant in Dounreay, located at a distance of 20km from MeyGen, will be used.

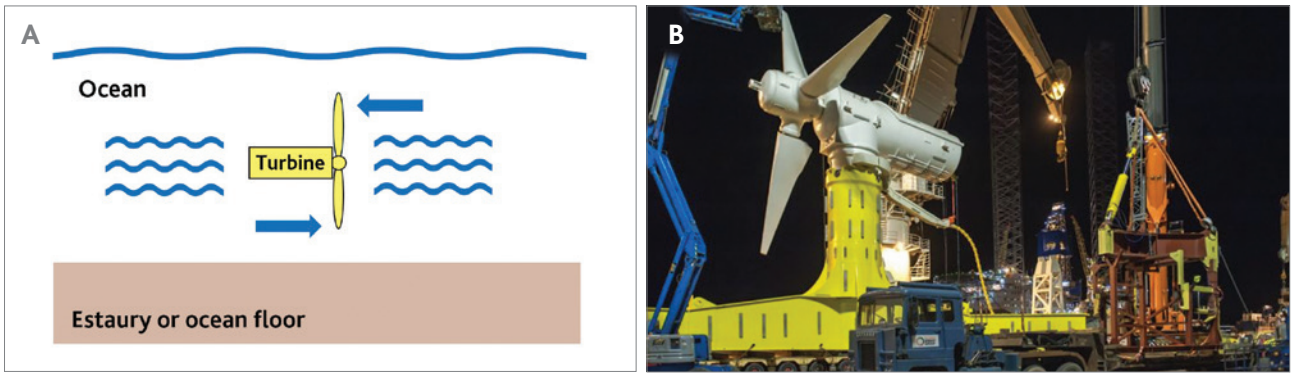

Figure 5: Horizontal-axis turbine. (A) Configuration of a horizontal-axis turbine. (B) One of the MeyGen Power Plant horizontal-axis turbines before loading on the ship for installation in the Pentland Firth (Scotland, UK).(Deign 2020)

ISLAND ELECTRICITY SELF-SUFFICIENCY: THE TIDAL KITE PLANT AT THE FAROE ISLANDS (DENMARK)

The Faroe Islands are inhabited by 50 000 people and are a self-governed part of Denmark. The archipelago is located in the North Sea halfway between Scottland and Iceland. The Faroe Islands want to reach 100% of renewable electricity production by 2030. (Barney et al. 2022)

In 2022 a tidal kite with a capacity of 0.1MW was installed as proof of concept at the Vestmannasund. It delivered reliable electricity to the national grid and was considered a success, so that in February 2024 a larger 1.2MW tidal kite was installed at the same location. The deployment of an array of 24 tidal kites with a total capacity of 30MW at the Hestfjord is planned during the next years. (Minesto 2024; Offshore 2024)

The wings of tidal kites use the hydrodynamic lift force created by the underwater current to move the kite. With an onboard control system, the kite is autonomously steered in a predetermined figure-of-eight trajectory (Figure 6A), pulling the turbine through the water at a speed several times higher than the actual current flow. Therefore, even low water speeds can be used for power generation. When the tide turns, the kite is re-aligned and starts to "fly" again as soon as the current is strong enough. The tidal kite consists of a turbine mounted on wings which are stabilised and controlled by rudders as well as a control unit for "flight" trajectories. The kite is tethered to an anchor on the seafloor (Figure 6B) (Minesto 2024).

The 1.2MW kite has a wingspan of 12m and a and a weight of 28 tons. (Minesto 2024) The low weight allows a cost-effective operation of the kites. Actual LCOE for tidal kites are not available yet, but Barney et. al. calculated LCOE for a tidal kite array of the Faroe Islands to be 8.79 €-ct kWh^{-1}. (Barney et al. 2022) Only after several years of electricity production and a sufficient number of plants installed, a robust value of LCOE can be determined. The comparably high LCOE may be attractive for remote island and installations in comparison to using fossil fuels for electricity production which have to be shipped there, thus increasing the LCOE of fossil fuel plants significantly.

WAVE POWER

Wind action, while having a low energy density, can accumulate energy in the top surface layer of the ocean over vast distances in the form of waves and can be used for electric power generation.

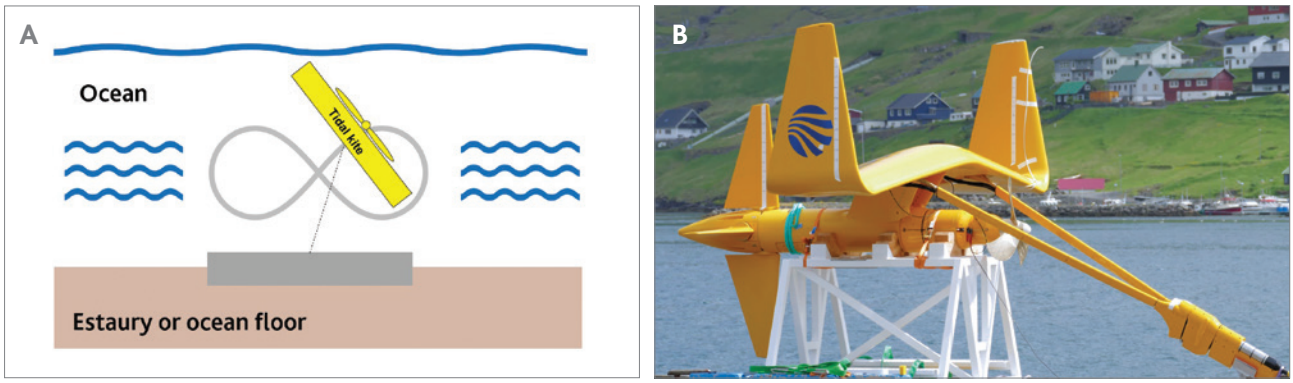

Figure 6: Tidal-kite turbine. (A) Configuration of a tidal kite turbine with schematic flow pattern. Modified after IRENA 2020 (IRENA 2020). (B) One of the 100kW capacity tidal-kites installed on the Faroe Islands (Denmark) (Frangoul 2020).

Generally, waves do last longer than the wind itself, as water – due to its higher density – reacts slower than air to changes in wind speed. Waves can also be regularly caused by tides, and ocean currents while wave-wave interactions, episodic landslides or tectonic movement can cause extremely large "freak" waves or tsunamis. In these cases, a wave power plant is automatically shut down to avoid damage, comparable to wind turbines in high wind-speed situations.

Wave energy contains kinetic and potential energy, and both can be harvested to produce electricity. Kinetic energy is mostly absorbed by moving bodies e.g. attenuators which stay on the surface of the water and move with it on a horizontal axis, while potential energy is used by "overtopping devices" which move up and down along their vertical axis. Some technologies use both energy sources e.g. point absorbers (IRENA 2020).

The energy content of waves is influenced by wave height, wave speed, wavelength (or frequency) and water density. Wave energy resources are spatially more evenly distributed than tidal sources, which is reflected in wave energy's large production potential. (IRENA 2020)

The theoretical global potential of wave energy is 30TWh per year which is approx. 10% of the current global electricity use of 30 800TWh. (Ritchie and Rosado 2020) Although varying in the short term as well as seasonally, waves can be forecasted from wind patterns and are widely considered a reliable and predictable energy source. (IRENA 2020)

Wave energy technologies have not seen a convergence towards one type of design which is a sign of early technology development stages. Over the years several working principles in all stages of technology readiness level (Tzinis 2012) have been developed (TRL values range from 1 to 9, the higher the number, the more commercialized is the product).

HAWAII'S (USA) EFFORTS TO BECOME INDEPENDENT FROM FOSSIL FUEL IMPORTS: THE OE35 OSCILLATING WATER COLUMN PLATFORM

Hawaii is the most petroleum-dependent state of the USA. The state government has set itself the goal of using 100% renewable energy by 2045. Additionally, the US-military is looking for ways to increase the energy efficiency and resilience of its deployed forces in the Pacific Ocean (Knodell 2021; OceanEnergy 2024; The Maritime Executive 2019).

The OE35 floating platform (Figure 7) could help to meet this goal. It is constructed by a cooperation of the US Navy, the US Department of Energy, and the Sustainable Energy Authority of Ireland. It's oscillating water columns technology funnels a discontinuous air stream driven by the movement of the waves through a one-way air turbine (Wells turbine). The special blade design turns the turbine in one direction only, regardless of the direction of the air flow (Figure 7A). The technology has reached TRL 8.(Knodell 2021; OceanEnergy 2024; The Maritime Executive 2019)

The OE35 barge was deployed in the Navy test site off Oahu (Hawaii) in 2019. The platform was designed by the Irish company OceanEnergy and constructed by a US shipbuilding yard. The barge is 38 by 18m large and weighs 825 tons, comparable in size to a small Navy vessel such as a mine sweeper. All moving parts are above water and therefore easily accessible for repairs and maintenance. It is expected to generate annually 1.25 – 1.75MWh which sounds reasonable for a 1MW turbine.(Knodell 2021; OceanEnergy 2024; The Maritime Executive 2019)

MEGAWATT-SCALE FLOATING WAVE ENERGY PLATFORMS: THE NANKUN PLANT IN ZHUHAI (GUANGDONG, CHINA) STARTS TRIAL OPERATIONS

The Nankun energy platform works on the oscillating bodies energy converter technology (Figure 8). The up/

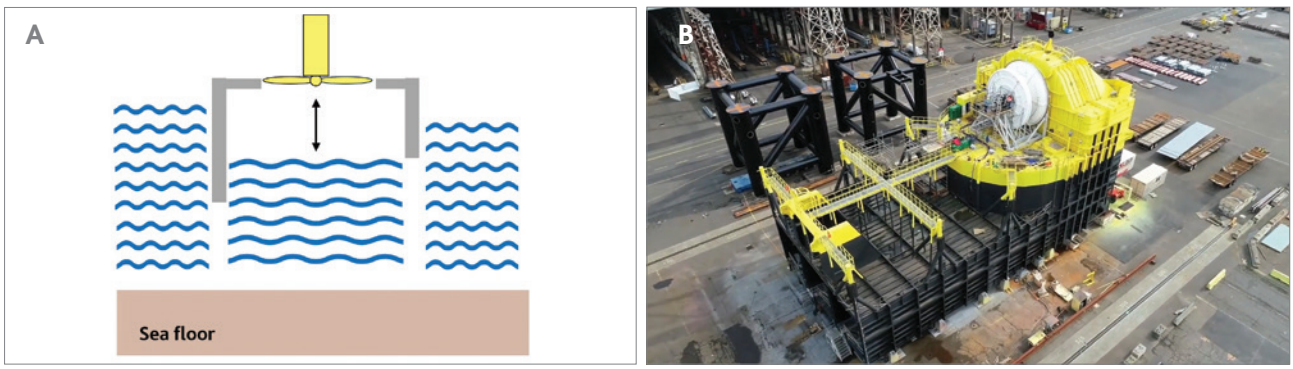

Figure 7: Oscillating water column technology. (A) Configuration of a typical setup. The water surface level changes caused by wave action push air through a wind turbine which works only in one direction. Modified after IRENA 2020 (IRENA 2020). (B) Picture of the OE35 barge, developed by OceanEnergy (Ireland). Submerged parts of the barge are painted black, yellow painted parts are above the water surface (OceanEnergy 2024)

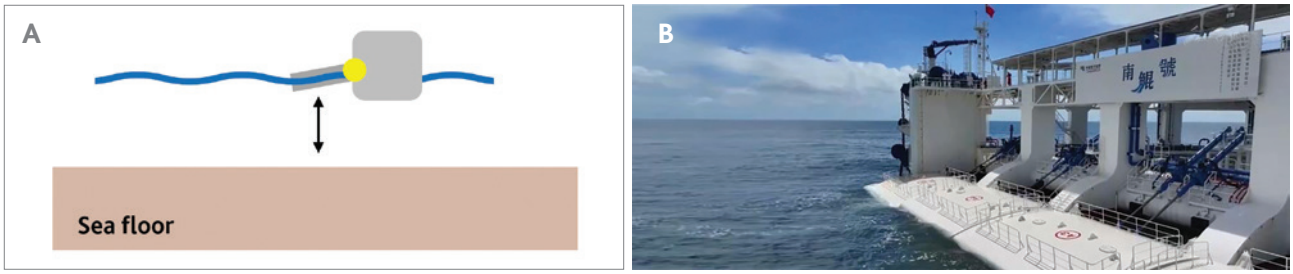

Figure 8: The Nankun wave energy platform. (A) Working principle of the floating wave energy platform. A large floating platform with smaller floating sides converts the up-down movement of the waves via hydraulic power to electricity. (B) Photo of China's first megawatt-scale floating wave energy generation device, called Nankun, in Zhuhai, Guangdong province (Yukun 2023).

down movement of moveable floating plates relative to a larger floating engine platform pushes and pulls pistons, which drive electric generators via a hydraulic engine. The technology has reached TRL 8.

The large triangular wave energy platform started its trial operation in June 2023. It has a length of 300m covering an area of 3 500m². The platform is semi-submersed and has a displacement of approx. 15 000 tons. The structure consists of a power generation platform, a hydraulic system, a monitoring system, and an anchor chain system that will allow it to be deployed in water depths between 30 and100m. The structure – labelled as a vessel – was built by the Chinese COSCO Shipping conglomerate (Braid Maritime 2023; Yukun 2023).

Each of the three sides of the main vessel body has five floating plates connected to it that are driven up- and downward by the movement of the waves (Figure 8). No crew is needed, as the platform is remotely controlled. Solar panels are also installed to generate additional energy. The device can generate up to 24MWh of electricity per day (Braid Maritime 2023; Yukun 2023).

The Nankun platform is a commercial prototype with emphasis on the commercial aspects. The successful establishment of the platform, three times bigger than a mid-sized frigate, shows that the stage of proof of concept for several constructional topics has been passed. The question to be answered is not whether it will generate electricity, but how much. The electricity production from movement of waves, transformed via the movement of pistons into hydraulic pressure and afterward with a turbine into a stable and continuous electrical current is the most essential and impressive aspect of the Nankun platform. (Braid Maritime 2023; Yukun 2023)

BUOY POINT ABSORBER ARRAY AT THE WEST COAST OF IRELAND: THE SAOIRSE WAVE ENERGY PROJECT AS A PRE-COMMERCIAL DEMONSTRATION PLANT

Point absorbers in the form of buoys can use both the kinetic and the potential energy of the waves. They are moored to the sea floor and can be arranged into arrays, forming multi megawatt plants. A combination with offshore wind farms seems favourable, as the grid connecting infrastructure can be used.

The Saoirse Wave Energy Project at the west coast of Ireland is a pre-commercial test and demonstration plant. At this location waves are created by wind and the tides. The plant uses an array of point absorber buoys from the Swedish manufacturer CorPower. They have successfully

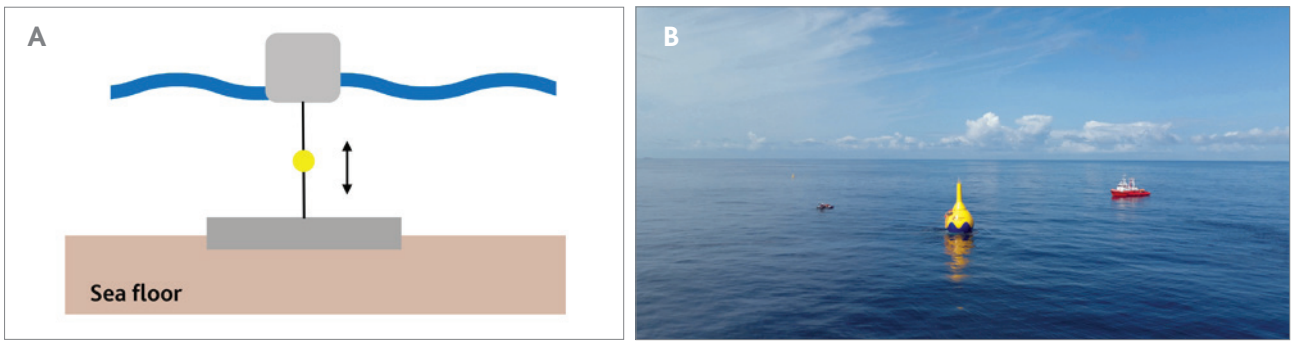

Figure 9: (A) Point absorbers use kinetic and potential energy for electricity generation from movement in all directions of the buoy relative to the mooring by a mechanical drive. The up/down motion is transformed into rotation which drives a generator. Modified after IRENA 2020 (IRENA 2020). (B) Newly installed point absorber as used in the Saoirse Wave Energy project. The vessel serves for size comparison and is used to fix the buoy to the seabed mooring (Saoirse Wave Energy 2024).

passed the test on Portugal's Atlantic coast, one of the most challenging marine environments.

The buoys use the kinetic and potential energy of the waves for electricity generation. The movement - up/down und sideways - relative to the mooring of the buoy is transformed by a mechanical drive into rotation energy which drives a generator inside the buoy. Each buoy is 9m wide and 19m tall and has a capacity of 300kW (Figure 9).(Saoirse Wave Energy 2024; CorPower Ocean 2021) If waves exceed a given maximum height, the internal mechanism is automatically disengaging to protect the system.

The power plant is deployed 4km off the coast of County Clare in Ireland. A capacity of 5MW is planned to be deployed until 2026, and an additional capacity of 25MW until 2028. Expected operation time is 15 years intended as a pre-commercial project. (Saoirse Wave Energy 2024; CorPower Ocean 2021)

The electricity producing network of buoys is in a pre-commercial development stage. The technology is mostly placed under water in a challenging high-wave environment. Whether the many moving parts of the technology will prove to be of low maintenance can only be evaluated after a significant running time. The same holds true for the mooring on the seabed which typically has a low impact on the ocean floor.(Saoirse Wave Energy 2024; CorPower Ocean 2021)

OCEAN THERMAL ENERGY CONVERSION

Oceans absorb the irradiation of the sun and store the energy as heat mainly in the epipelagic (sunlight) and mesopelagic (twilight) zones extending down to approx. 200m and 1000m depth, respectively. Ocean Thermal Energy Conversion (OTEC) uses the temperature difference between the warm surface (down to 50m depth) and the cold deep-sea (starting below 800m to 1000m depth) and converts it into electricity. The minimum temperature difference of the two ocean water bodies must be >20°C. Because deep sea ocean water is at a constant temperature of 4°C, the ocean surface temperature must be at least 25°C without significant seasonal variations and the sea must be at least 800m deep to reach the deep-sea layers. Such conditions are only present in tropical regions between latitudes of less than 30 degrees north and south. (IRENA 2020; Tethys 2025b)

Even though restricted to the tropics, the global potential of OTEC is the largest of all ocean energy sources with 44 000TWh per year of continuous power. Besides it's uniquely large potential, OTEC's main advantage is the ability to provide a non-intermittent, continuous power supply. (IRENA 2020)

In the simplest technical configuration, warm surface water is used in a closed-cycle system to heat a working fluid with a very low boiling point (e.g. butane or ammonia). The gas then drives a generator and is condensed by coming into contact with cold, deep-sea water in a condenser and is pumped back into the closed system (Figure 10A). (IRENA 2020) More sophisticated versions of the technology are available. Globally, several test plants at universities and research centres are operational. Six OTEC plants were globally in operation in 2021 and another twenty are currently in various planning stages in all tropical oceans. (Kim et al. 2021)

RESEARCH AND DEVELOPMENT COOPERATION FOR NEW TECHNOLOGIES AND ENERGY INDEPENDENCE: THE KAILUA-KONA OTEC TEST PLANT IN HAWAII (USA)

The OTEC facility in Kailua-Kona (Hawaii, USA) has been

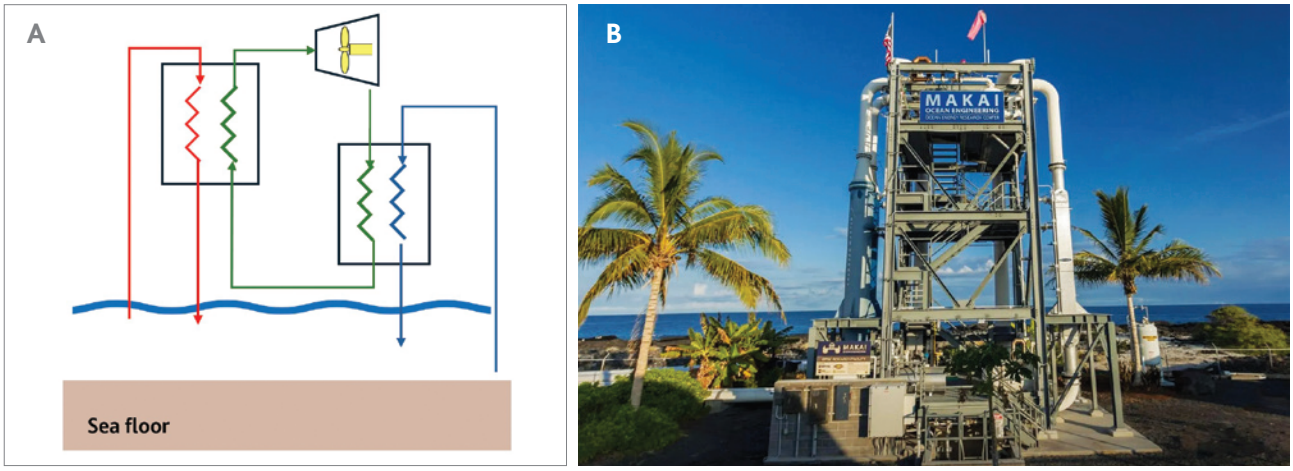

Figure 10:Ocean thermal energy conversion (OTEC) (A) Working principle of a closed-cycle system. The working fluid (green) is heated and vaporised (left) by warm surface sea water. The vapor drives a turbine (top) which drives a generator. The working fluid is cooled by cold deep-sea water in a condenser (right). Modified after IRENA 2020 (IRENA 2020), (B) On-shore OTEC test facility in Hawaii with a capacity of 100kW (Makai Ocean Engineering 2024).

in operation since 2015. It is run by a cooperation of the private company Makai Ocean Engineering, the U.S. Navy's Office of Naval Research, and the University of Hawaii. It has a capacity of 100kW and is also capable of providing thermal energy for heating and cooling in addition to producing electricity.(Makai Ocean Engineering 2024; U.S. Energy Information Administration 2024)

SALINITY GRADIENT

Energy from the sun not is not only stored as heat in the oceans but also stored as chemical energy in form of a concentration of ions. While freshwater influx from rivers has a low concentration of ions, the continuous evaporation over the oceans results in an ion-free water vapour flow to the atmosphere and an increase of the ion concentration in the ocean water.

The mean salinity of the oceans is 3.5% with some variations across the globe. It is lower in regions with freshwater influx from rivers or glaciers and low evaporation e.g. in the proximity of the poles. Regions with a lack of precipitation or river influx and high evaporation show higher salinity. As the amount of retrievable electricity is proportional to the salinity gradient, freshwater-seawater systems are most efficient for electricity production. Salinity plants can produce electricity continuously. However, the geographical requirements are significant and therefore, the estimated global potential of 1 650TWh yr^{-1} is small in comparison is small in comparison to the other ocean power technologies (IRENA 2020; ESA 2019).

Currently two technologies are being tested and applied: Pressure retarded osmosis (PRO) and reversed electro-dialysis (RED). Both technologies are on low TRL levels and need ion selective membranes to separate the salty from the freshwater to allow ions to move from the higher to the lower concentration. Such membranes are currently not commercially available in the needed quantities. The technology remains in conceptual and test stages and is significantly less mature than tidal, wave or OTEC.

The RED system makes direct use of the salt ions in the seawater and bypasses the need for a turbine and any moving parts. Energy losses due to friction are non-existent, which is why the technology shows a high efficiency. In seawater the dominant ions are sodium (Na+) and chloride (Cl-). The RED system contains ion selective membranes for both, positively charged cations (e.g. Na+) and negatively charged anions (e.g. Cl-). A pair of electrodes bridges the membranes. When sea water flows between a positive and a negative selective membrane with freshwater on the other side of the membranes, the ions from the sea water will migrate through the respective membrane to the fresh water. One side will become positively charged, the other side negatively thus creating an electrochemical cell (Figure 11A).

THE FIRST SALINITY GRADIENT PLANT IN OPERATION SINCE 2014: THE RED POWER PLANT ON THE AFSLUITDIJK FLOOD PROTECTION DAM IN THE NETHERLANDS

In 1932 the 20km long Afsluitdijk dam located between the Dutch provinces of Friesland and North Holland next to the North Sea was built to protect the country from storm surges. The detached water body quickly became a freshwater lake because of a river flowing into it and was named IJsselmeer. In 2014 the dam was enlarged to host the first RED technology salinity gradient electricity plant

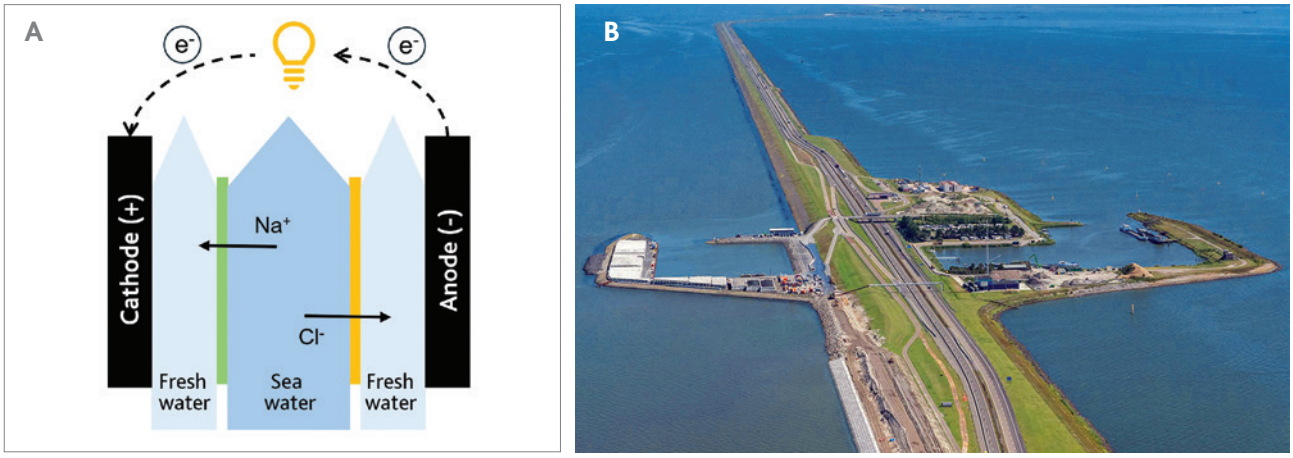

Figure 11: Salinity gradient plant. (A) Schematic diagram of the RED-technology with two differently selective membranes. Green: Cation selective membrane. Orange: Anion selective membrane. Black: Pair of electrodes. The Cathode is positively charged and the place of reduction, respectively the uptake of electrons. The anode is negatively charged and the place of oxidation, respectively the loss of electrons. Modified after IRENA 2020 (IRENA 2020). (B) RED plant on the Afsluitdijk dam in the Netherlands. Left in the picture is the saltwater side of the North Sea, right is the IJsselmeer freshwater lake. The power plant is located at the freshwater side of the dam. Sea water is pumped via a pipeline to the plant and the brackish waste water is pumped back to the seaside by a separate pipeline (IRENA 2020; REDstack 2024).

with 50kW capacity. Using the existing dam reduced the investment costs of the plant significantly (Figure 11B). The plant is theoretically able to run on a permanent basis (8760 h yr^{-1}); however, all power plants are at least one month per year shut down for maintenance and repairs which results in this case in a capacity factor of 90%. Although the plant is running successfully, funds to build a larger plant are currently not available (REDstack 2024; IRENA 2020; Encyclopaedia Britannica 2025).

ENERGY SECURITY AND RESILIENCE

Several technologies for using the energy potential of the oceans are currently in use with the majority of them in a more or less advanced prototype or experimental phase of application. There is no doubt that some of these technologies will reach maturity. The key to further success of ocean power will be to secure the capital investment needed to reach TRL 9. Governments may invest in such technologies because they provide strategic energy security and thus resilience for nations and help reducing the environmental impact of power generation while private investors must be sure that the technology promises a return on investment. In a best-case scenario, all aspects can be addressed by ocean power technologies and national and private interests are covered.

In the following we discuss the challenges and options for strategic energy security, resilience and environmental impacts. In a second article we will then address the question of costs, investments and best locations for large-scale integration of ocean power into the electricity grid and the global energy mix.

OCEAN ENERGY TECHNOLOGIES AND THE NEED FOR BASELOAD CAPABILITY

Modern societies have high energy demands and need sources of very flexible electricity supply because the instant electricity demand varies hugely on a daily (day/night), weekly (working days/ weekends) and seasonal basis (winter/summer). This requires the presence of plants which can be operated on demand and on response timescales reaching from seconds to hours. Electrical grids dominated by renewable energies without storage capabilities generally lack plants with so called base-load capabilities. These plants operate constantly with response times of hours and cannot be shut down completely on a short time scale (e.g. coal plants).

To demonstrate the temporally varying electricity demand and the need for a baseload capability the energy production vs. consumption in Germany is shown for a full week during summer and Winter in 2024 with the latter covering a period of dark doldrums also known as "Dunkelflaute" days (Figure 12). During the summer of 2024 the production of renewable electricity exceeded the demand significantly, especially around noon, while during calm periods at night the electricity production was low. In winter – especially during the dark doldrums – the electricity demand of Germany could not be covered domestically. Dark doldrums occur for a few days annually. Longer periods of several weeks may happen every 3 to 5 years, when neither wind nor solar power plants produce sufficient electricity.

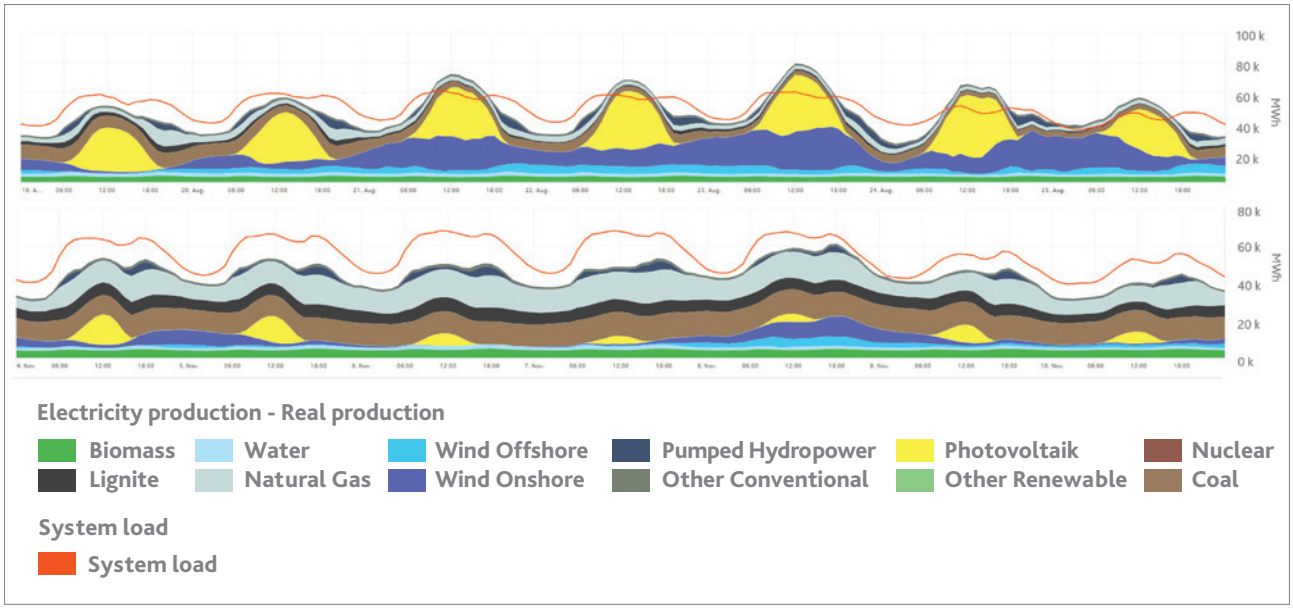

Figure 12: Energy production and consumption within Germany during a week in summer and winter of 2024. (A) Week from Monday 19th to Sunday 25th of August (summer in the northern hemisphere) and (B) Week from Monday 4th to Sunday 10th of November 2024 (winter in the northern hemisphere and including some days of dark doldrums)(Bundesnetzagentur 2025). The electric power demand (system load) is during most days higher than the power produced by German power plants and must be covered by imports.

DARK DOLDRUMS AND BASELOAD CAPABILITY IN GERMANY

Especially in winter during the dark doldrums, Germany imports large quantities of electricity. During these periods electricity costs in Germany as well as in the European synchronized grid zone, (ENTSO-E 2022) can increase dramatically. During summer, when solar power production is huge, Germany becomes an electricity exporter especially to Norway through the NordLink Power line (Fischer 2021; TenneT TSO GmbH 2020) and to France when cooling capacity for the French nuclear power plants is diminished (Comptes Rendus de la Commision des Finances 2023).

In the case of highly industrialised countries a non-wind and non-solar predictable and controllable renewable power sources integrated into the electricity mix - such as ocean power- (Table 2) could allow the decommissioning of "reserve power plants". These are generally fossil fuel based with high productions costs per kWh because of their low annual running time.

Excess electricity from wind and solar during peak production in summer could be directed to e.g. the production of green hydrogen (Lauf 2020; Lauf and Zimmerman 2022).

Baseload capacity in electrical grids dominated by renewable power plants without storage capabilities such as wind and solar-PV is minimal. In contrast, some ocean power technologies can provide a predictable and sometimes even controllable 24/7 power production and are discussed with respect to their electrical grid stabilizing potential.

Ocean thermal energy conversion (OTEC) and Salinity Gradient technologies are potential baseload technologies because both provide electricity permanently and are at the same time controllable and flexible in responding to varying electric demands. OTEC, while limited to the tropics and a sea depth of >800m has the environmental advantage that it can be installed offshore and thus does not compromise shallow water ecosystems and the coastline.

While tidal power technologies are also long term predictable, only tidal range power plants with a reservoir provide storage, controllability and flexibility and thus fulfil the requirements for baseload power plants.

Tidal stream and tidal range plants without reservoir lack energy storage capability and thus controllability. While they can serve as a valuable energy source for predictable temporal energy production, tidal range and tidal stream power technologies do not fulfil the requirements for baseload applications unless connected to large mid- to long- term electric power storage facilities which are still extremely expensive.

Wave power lacks all features mentioned above and might be useful as an additional energy source if the baseload capacity is provided by other technologies.

In spite of the still high investment costs, ocean power technologies are already used successfully on islands and small or remote coastal communities because they reduce the dependence on expensive fuel imports and associated supply logistics.

GLOBAL USABILITY OF OCEAN POWER TECHNOLOGIES

All described technologies rely on specific physical environmental conditions and on water in its liquid state of aggregation.

In the high latitudes and the arctic regions icebergs and pack ice endanger ocean power plants. Icebergs may reach heights above water of more than 100m and below water up to 700 meters. Pack ice is much shallower, both

Technology	Predictability of production	Storage capacity	Controlability	Flexibility
Ocean Thermal Energy Conversion (OTEC)	Permanently available	Thermal energy	Yes	Yes
Salinity gradient	Permanently available	Salinity	Yes	Yes
Tidal range with reservoir	Long-term	Reservoir	Yes	Yes
Tidal range	Long-term	No	Yes	No
Tidal stream	Long-term	No	No	No
Wave power	Short-term	No	No	No

Table 2: Characteristics of renewable ocean power technologies for electricity production sorted in descending order from the best to the least fit.

above and below the water level and may be driven as drift ice by waves, wind, tides and currents towards power plants and thus damage or destroy them. As a consequence, arctic regions and the drift ice areas of the oceans appear unsuitable for ocean power plants. This excludes at last 12% of the global ocean areas from ocean power technologies.

OTEC plants have the highest prognosed power production potential and need a minimum surface water temperature of 25°C and access to water of 4°C in about 800 to 1000m depth.(IRENA 2020) The tropical zones of the Indian and the West Pacific Ocean have the highest seas surface temperatures. Some locations outside of the tropics e.g. the coastlines of Mexico and the Caribbean or the Chinese Sea are also apt for OTEC (Figure 13). This area will certainly increase further poleward due to the warming climate.

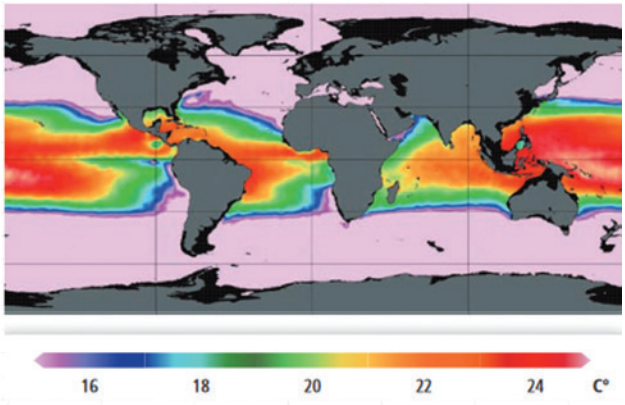

Figure 13: Global Sea Surface temperatures averaged for 2003–2011. Areas with an ocean surface temperature all year round above 25°C are potentially apt for OTEC technologies. (Lewis et al. 2011)

Most challenging are suitable locations for building salinity gradient plants. Fresh and saltwater sources must be available in close proximity to each other, and these conditions are normally found on coastlines with large rivers. Conflicts over freshwater use is difficult to avoid which is problematic in dry and hot regions. These coastal locations also tend to be densely populated. Installing salinity gradient plants is theoretically possible near artificial saline systems e.g. using high salt content brine from desalination plants or high salt content brine from lithium extraction plants, but environmental concerns might be difficult to overcome.

For military applications, small autonomous offshore power systems which offer electric power in the 10W to 1MW range can provide communication and data services for underwater vehicles and open-ocean environmental sensors (Figure 14). Also, remote military bases may profit from ocean power systems providing electricity, but the need for resilience will allow only a supportive role for the energy generation.

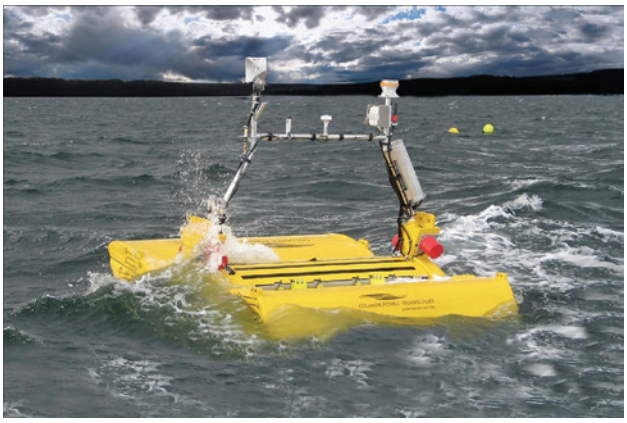

Figure 14: The SeaRAY offshore wave power system designed for localized power-generation and data services connecting to unmanned underwater vehicles and ocean-dwelling environmental sensors. (Schmitz 2025)

ENVIRONMENTAL CONSIDERATIONS AND IMPACTS OF OCEAN POWER TECHNOLOGIES

Any human activity has implications for the environment. Electricity production from renewable sources helps to prevent the release of greenhouse gases from fossil sources into the atmosphere. However, this advantage in mitigating the current global warming trend must be balanced with negative effects on the ocean's ecosystems.

Many of the described technologies only exist as prototypes or in small commercial numbers. Therefore, environmental studies evaluating their environmental impact on a larger scale have not yet been performed for all the technologies presented in this article. In the following the already proven side effects of technologies described in this article will be discussed, while large scale implementation of ocean power plants may cause further, often unintended environmental problems.

Large-scale ocean power infrastructure may interfere with activities such as fishing and shipping, endanger marine wildlife via risk of entanglement, or cause debris and pollution as pump material malfunctions and maintenance services to fix broken pipes may transport invasive alien species. (Barboza et al. 2018; National Academies of Sciences 2022; Röschel and Neumann 2023)

Specifically, the creation of magnetic fields by electricity generating and transporting devices can disorient organisms which rely on the magnetic field of the earth for orientation while low frequency noise from machinery is a general problem for many marine organisms (as well as military sonars) and not limited to ocean power generation technologies. The oscillating water column wave power technology as described in the OE35 is noisy and may not be tolerated near settlements.(Tethys 2025c)

Tidal range technologies require large barrages and

change the sedimentation dynamics and the ecology of the blocked river, inlet or bay In the case of a lake forming dam with sufficient influx of freshwater and turnover of the lake water, the waterbody can turn from salt water into a freshwater ecosystem, as had happened with the IJsselmeer. (Encyclopaedia Britannica 2025) However, without sufficient freshwater but high waste water influx the lake can turn into an ecological disaster zone as was the case of the South Korean plant. Only after severe interventions following the completion of the dam and a change in perspective in terms of the kind of the ecosystem, a viable salt water ecosystem was created. (Park and T. S. Lee 2021; K-Water 2024) In the case of dams on river outlets (AIP Conference Proceedings 1850; Schneider et al. 2017) the sedimentation patterns are changed and the migration of fish may be obstructed, as was the case of the river Rance in France. (EDF 2024; Boretti 2020) Often these artificial water bodies attract tourists which can cause additional environmental problems.

Tidal stream and wave power technologies must be anchored to the ocean floor which locally destroys the seabed ecosystem. Tidal stream technologies rely on relatively slow-moving rotors or kites submersed in the water. While no casualties of large fish, seals, dolphins or whales have been reported, other possible disturbances such as altered water flow patterns are under investigation.(Tethys 2025a)

The most significant environmental impacts might evolve from a large-scale use of OTECs. Cold, nutrient rich deep-sea water is pumped to the ocean surface (artificial upwelling) while warm, carbon enriched surface water will be pumped to the deep sea (artificial downwelling). This will change the density structure of the ocean and the ocean circulation over tens of kilometres.(National Academies of Sciences 2022)

The artificial downwelling causes an (un-)intentional transport of dissolved CO_2 and the transport of surface heat, nutrients and oxygen into sub-surface water (Stigebrandt et al. 2015) with so far unknown changes in the deep-sea biodiversity. Artificial upwelling on the other hand fertilizes surface waters and stimulates phytoplankton growth. A potential positive effect of this is the long term (centuries to millennia) storage of photosynthetically fixed atmospheric carbon when the dead phytoplankton sinks to the deep-sea ocean floor. Also, the enhancement biological production (Oschlies et al. 2010) could impact fishing or mussel farming. (Handå et al. 2013; Casareto et al. 2017; Ortiz et al. 2022) Artificial upwelling leads to cooler surface water temperatures and might reduce the stress on thermally sensitive ecosystems like, coral reefs (Sawall et al. 2020; Schneider et al. 2017) but cold deep-sea water also lowers the pH value of surface water and could endanger marine ecosystems by acidification.(Pan et al. 2016)

OUTLOOK

As many as 2.4 billion (109) people, representing 40% of the global population, live within 100km distance from ocean coasts or on islands (IRENA 2020). Supplying them with renewable energy from the ocean is possible. The largest, almost untapped renewable energy source is the thermal energy of the oceans which can be converted to electric power by Ocean Thermal Energy Conversion technologies. The second largest ocean energy source is energy stored in waves.

Both technologies can be deployed offshore and in the open sea, thus not being limited to the vicinity of coastlines and shores. Thermal energy conversion in the ocean is limited to tropical and subtropical areas, while wave energy can be exploited in most ice-free areas, thus providing a much larger geographic potential.

Future large-scale application of these two technologies faces two major challenges: power transmission and environmental concerns. The generated electric power must be transmitted from the producing devices in the open ocean to the consumers at the coast, often across large distances. This involves huge investment and maintenance costs for energy transmission.

Especially for thermal energy technologies, the environmental concerns reach from immediate negative effects on fishery and marine life to concerns of irreversibly by the authors changing the ocean water thermal properties of surface and deep-sea regions.

The implementation of any ocean-based installation, whether floating or fixed, must be approved by the governmental authorities with respect of environmental and navigation safety. Power plants and transmission lines may obstruct existing and potential new shipping routes as well as the environment.

Power production plants are typically run by private companies and are connected to a larger electric grid system. Aspects of choosing the best locations and a comparison of electricity production costs for the different ocean power technologies will be covered in a separate publication.

However, for such installations each nation also must decide whether these plants and power lines are considered as Critical Infrastructure and require additional protection provisions against cyber or kinetic attacks. Deep-sea cable security and protection has come recently under increased scrutiny.

This involves not only the costs of security measures against potential terrorist attacks but also the need for planning military protection of this energy infrastructure if deemed critical for a nation in a conflict situation.

Additional issues may arise from the regulatory and legal framework which can present challenges in the high seas due to legal uncertainties, regulatory gaps, jurisdictional disputes and limited protection against sabotage of offshore installations and subsea cables.

Nations located in higher latitudes, namely many members of NATO will not be able to cover their future renewable energy demand by wind and solar power generated within their own territory alone. Importing electric power from other regions or open oceans located at lower latitudes will not only pose additional costs and risks for their nation's energy security but will inevitably create new geostrategic and geopolitical dependencies.

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Blurred Lines: The Role of Security and non-Security Actors in the Energy Landscape

By **Marie Becker and Michael Kalis**

INTRODUCTION

This article explores how the dual evolvement of the concept of energy security on the one hand and of the threat landscape it faces has resulted in the convergence of traditional security- and non-security-actors' mandates and activities and, as a result, in a blurring of erstwhile clear-cut roles. The analysis situates these shifts within the broader energy transition, where the often-cited Energy Trilemma stipulates a transformation along the principles of energy security as well as sustainability and equity. The Baltic Sea Region, in which these transformations have been unfolding in a particularly pronounced manner and – with regard to transforming the energy security landscape – in the context of extremely high stakes, serves as a regional lens of focus.

1. ENERGY SECURITY: THE INTRODUCTION OF A CONCEPT AND ITS CONTEXTUALIZATION

Energy security is a concept of many dimensions, even more – context-dependent – definitions [1,2], and associated with an accordingly diverse set of possible tactics and measures that may work towards its achievement. From the perspective of NATO and its member states, the concept had its first major appearance on the geopolitical stage in the context of the Yom Kippur War of 1973, in which energy exports were used as a bargaining chip resulting in an oil price crisis in the United States and many Western European countries [3,4]. The International Energy Agency (IEA) founded in the aftermath (1974) consequently focused its energy security efforts on the dimensions of availability (i. e. uninterrupted sufficient supply) and affordability (price level and stability) mainly of oil [4,5]. This focus on (oil) security of supply has remained prevalent in energy security debates and policies ever since [3,6,7,8]. The World Energy Council for instance still speaks of energy security as "the nation's capacity to meet current and future energy demand reliably, withstand and bounce back swiftly from system shocks with minimal disruption to supplies" [9].

Just like the concept itself, the instruments for ensuring energy security had, until recently, remained largely static. Informed by the experiences from 1973, diversification (both of sources and in terms of energy mix) and energy efficiency were usually emphasized in order to reduce delicate dependencies – an approach, that is still central to the European strategy [10]. In principle, this also applies to the Baltic Sea Region [11,12]. Especially in the Nordics, however, national approaches have further prioritized stockpiling, owing to specific vulnerabilities emanating from seclusion and extreme weather[1]. Furthermore, based on the historical development of the region, system integration and transnational cooperation have always constituted a central part of energy security policies [11,12]. In fact, following the World Energy Council, it

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1 See for example the security of supply act [13] that Finland notified as a transposition measure in relation to EU Directive 2008/114 (see below).

has been through (timely) system integration and transnational cooperation that the national states within the Baltic Sea Region managed to cope with the energy crisis during the year 2023-2024 [14].

2. THE INITIAL SEPARATED ROLE OF SECURITY AND NON-SECURITY ACTORS IN ENERGY SECURITY AND TRANSFORMATION

Following the aforementioned trajectory of the concept and the according assortment of (policy) instruments, energy security largely remained within the bounds of the civilian realm. This has been further reinforced by the advancing liberalization, privatization and decentralization[2] of energy production and distribution [15,16,17]. The resulting proliferation of a diverse set of actors in the areas of system stability, security of supply, and ultimately energy security has invited the EU to extend its already strong role as regulator and central coordinating authority with regards to energy policy.

That is not to say that military actors had no business with energy security. However, their focus was more narrowly set on energy security as an enabler of military capacity – the fuel to keep tanks, ships and planes moving and the electricity to keep communication, weapon and surveillance systems running [4]. For traditional security-actors (NATO and its national counterparts), the concern was less about the "conventional paradigms" [4, p. 1] of energy security as relating to state, economy and society as a whole. Overall, traditional security actors were thus taking care of traditional security matters and traditional non-security actors were taking care of traditional non-security matters. This set-up, however, left one marked gap in terms of responsibility and leadership: the matter of critical energy infrastructure resilience. While infrastructures, important to societal, but not military, functions, were considered largely out of scope from the perspective of military actors [18], civilian actors saw for themselves no part in measures of infrastructure protection suited to thwart violent, state-sponsored attacks[3]. In the case of the EU, any activity regarding critical infrastructure protection was further hindered by its members' reluctance to surrender any authority in a field so intimately tied to questions of national security and sovereignty [20-24].

3. ONSET OF A TRANSFORMATION? NATO AND EU ENTERING THE FIELD OF CRITICAL ENERGY INFRASTRUCTURE PROTECTION

More recently, however, the continuous change of energy systems and different crises (e. g. COVID-19 pandemic) have led to a more nuanced and resilience-focused conceptualization of energy security [14, p. 11]. Along with the concept itself, the range of instruments available and appropriate for civilian and military actors alike expanded. Shortly after the turn of the millennium, both NATO's and the EU's stances on the matter of energy security underwent marked change.

For NATO's part, the admission of seven countries formerly belonging to the Soviet Bloc, and in particular of the Baltic states also brought a group of strong advocates in favor of NATO including energy security in its portfolio [25,26]. Following the call of the 2006 Riga Declaration, a first respective mandate was given at the 2008 Bucharest Summit Declaration [27] and fortified in 2010, appearing for the first time in a NATO Strategic Concept [28, cf. 25]. Throughout, a strong emphasis was laid on the development of NATO capabilities to contribute or support the protection of critical energy infrastructure [26]. A second factor that drove NATO initiative ahead consisted in the changing threat landscape critical energy infrastructure was facing. The proliferation of terrorist attacks and acts of hybrid warfare targeted specifically at critical energy infrastructure left civilian actors unable to respond adequately [cf. 19]. The EU, for one, had never been endowed with its own hard power capabilities, essentially inviting traditional security-actors to get involved in a complementary way [26] NATO's claim to authority in the field was further aided by advancing digitization and the close relation between cyber security and energy security, in the former of which NATO has been generally "perceived as having a stronger mandate even by countries [...] who are skeptical when it comes to the role of NATO in energy security" [25, p. 448].

The changing and increasingly transnational nature of the threats facing critical energy infrastructure also finally summoned the EU to take legislative action. While the terrorist attacks on the transport systems in Madrid (2004) and London (2005) are generally cited as the impetus for *Directive 2008/114 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection* [29-31], the energy sector was also included in the directive's scope, owing to its – even then – highly pronounced position in a system of cross-sector interdependencies [32,33]. The EU had taken a first step into an area of security policy formerly exclusive to national authority.

Nonetheless, in terms of introducing a truly supranational approach, this first round of EU legislation remained rather modest as did its real impact [34,35]. Similarly, NATO's ambitions in the field were proclaimed limited to finding a "niche", within which some value might be added to other actors' activities [26, p. 5].

4. TRANSFORMATION IN FULL SWING?: INCREASINGLY BLURRED LINES IN ENERGY SECURITY LANDSCAPES

2 A result of the ongoing transition towards renewables.

3 See for example the explication in [19], but also the statements of industry associations concerning the German government's drafts for a new law on critical entity resilience 2024, https://www.bmi.bund.de/SharedDocs/gesetzgebungsverfahren/DE/KRITIS-DachG.html (accessed Jan. 05, 2025).

Today, things are different. In recent years, issue salience has continued to grow at speed as geopolitical tensions in the EU's immediate neighborhood have mounted and hybrid threats moved to the center of attention, with the sabotage of pipelines to Russia's attempt to redraw its maritime borders marking the Baltic Sea Region as one of the hot spots [37]. As energy exports have become weaponized and energy infrastructure become a core target of attack, the close linkage between energy security and military defence, often referred to as the energy-security nexus, has moved to the center of current energy policy in the Baltic Sea Region and beyond [cf. 37,38]. Crucially, this nexus is increasingly reflected in blurred lines between the actors and their competencies in the area of critical energy infrastructures.

In the same year that Russia launched its full-scale invasion of Ukraine, the EU adopted a new, much more ambitious directive on the resilience of critical entities (2022/2557) [39], which already incorporates strong supranational elements [cf. 32]. In the wake of the prominent acts of sabotage against NordStream, the European Council concurrently issued a recommendation to emphasize the directive's importance and to push members for expeditious and extensive implementation thereof [33]. Against the same backdrop, NATO has taken several steps to lay the basis for acting on its newly extended mandate, for instance via the launch of a new Maritime Centre for Security of Critical Undersea Infrastructure, resolved upon at the Vilnius Summit 2023 [40]. In the summit's communiqué, NATO further explicitly reiterated the potential of (hybrid) attacks on critical energy infrastructure to trigger Art. 5 of NATO's Washington Treaty [40], due to energy's extraordinary importance to the functioning of modern societies. With both actors thus more decisively beholding the resilience of critical energy infrastructure as a matter within their realm of responsibility, the formerly clear distinction between security- and non-security-actors has begun to disintegrate. Evidence for this convergence can be found not least in the implicit acknowledgement thereof by the actors itself, which is most prominently expressed via the NATO-EU Structured Dialogue on Resilience and the therein embedded formation of a joint taskforce on the matter [41].

This amalgamation of security and non-security spheres is also mirrored on the national level. Here, non-security related, and often private, operators and owners of critical infrastructure suddenly find themselves compelled to perform at least some security functions [42]. This close interplay between civilian and military matters is not so new in some countries ("civil preparedness", e. g. in the Baltic states), while it might indeed for others even require a rethinking of civil-military relations (e. g. Germany)[4]. At the same time, states need to re-evaluate where, to what extent and under which circumstances military resources are to be deployed for the protection of civilian infrastructures.

5. STEERING THE TRANSFORMATION OF ENERGY SECURITY: A CHALLENGE OF COOPERATION AND COORDINATION

Acknowledging the aforementioned events and developments one has to conclude that on the one hand NATO has entered the energy transition and transformation and the EU has included traditional security policies within its energy transition and transformation agenda. In doing so and in embracing this phenomenon of securitization within the energy transformation [cf. 11] also on the national level Europe apparently has all hands on deck. In expanding their common understanding of energy security [cf. 37,38] and in introducing new actors and new tasks within the energy transformation NATO and the EU do not only introduce a new layer to transforming the energy system but also increase the complexity in steering this transformation. Multi-level and multi-stakeholder dialogue, coordination and cooperation are the very foundation of a successful transformation.

First and foremost, crucial questions of principle must be answered to define the distribution of tasks, responsibilities, costs and risks as the basis on which efforts can be streamlined and cooperation institutionalized [cf. 44]. This need for discussion and clarification is particularly pronounced when it comes to the interplay between the state and (private) operators and owners of infrastructure: While EU members yield legislative power and carry ultimate responsibility for their citizens, expertise often rests with infrastructure operators and owners. These, in turn, find themselves unwilling to spend more on security than absolutely necessary from a business-perspective ("public-private dilemma" in critical infrastructure protection; see for example [45]) as well as unable to respond to anthropogenic malign threats such as terrorism and hybrid warfare, where law enforcement or even military capacity is needed. Moreover, actionable intelligence lays mostly scattered among all actors, due to the absence of the necessary procedures, infrastructure and trust for timely and targeted sharing[5].

The breaking down of traditional lines between security and non-security actors in the context of critical infrastructure resilience has thus brough the challenge of public-private, civil-military and national-international coordination to the forefront. While EU and NATO as well as different actors on the national level are in the process of negotiating these questions, the challenge extends to even more basic matters such as the quest for a common language

4 A pronounced lack of clarity regarding responsibilities and competence of military, law enforcement agencies, civil protection authorities and private entities is reflected in the expert statements on the debate in the German parliament on a possible marine security law (accessible at https://www.bundestag.de/dokumente/textarchiv/2024/kw12-de-bundespolizei-see-993254, accessed Jan. 05, 2025) and has been analyzed in detail in [43].

5 A challenge underlined in multiple expert interviews conducted in Q4 2024.

6 This even applies to the report of the joint NATO-EU taskforce [Taskforce Report]. Examples of sticky national concepts include "object of state importance" in Lithuania and "vital services" in Estonia (for both, see wording in notified transposition measures under https://eur-lex.europa.eu/legal-content/EN/NIM/?uri=CELEX:32022L2557, accessed Jan. 05, 2025), which formerly replaced [cf. 35] and now co-exist with EU concepts.

and common methodology. The EU's newest conceptual invention of taking critical entities into focus, has so far not inspired much reflection on part of NATO and national governments that still widely refer to critical infrastructure or even completely disjunct national concepts[6].

6. OUTLOOK AND RECOMMENDATIONS

It is thus of crucial importance that these ongoing debates on all levels occur in constant cross-reference and that the procedures and institutions they generate work with and speak to each other. It is not enough, for instance, for EU members to transpose Directive 2022/2557 and thereby defining obligations for infrastructure operators and owners. Rather, these obligations must be situated within an overarching concept of multi-stakeholder-cooperation cross-cutting sectors of energy and (traditional) security.

In this context, it is unfortunate that EU members are – qua directive – required to present a national strategy on the resilience of critical entities only in 2026, one and a half years after the implementation deadline. In other words, according to EU law, members are supposed to lay down rules for operators and owners in the absence of a comprehensive and strategic national approach to the issue. Thus, members should expedite the strategy process. In this process, they must build on their transposition of Directive 2022/2557 and clearly define the ways in which state actors – civilian and military alike – should take action to complement and support the measures required of operators and owners. These ways, in turn, would need to accord with international efforts, such as those led by NATO and the role that the specific state aims to play therein[7].

As much as NATO and the EU must craft a joint and coherent framework for their members to collaborate within, just so must individual nations avoid the compartmentalization of public versus private and military versus civilian spheres. Only where actors speak the same language, where they have general knowledge of each other's activities and capacities and where they all work towards joint strategic goals, will overlapping spheres of responsibility generate synergies rather than duplication, hindrance and confusion.

More generally, discussions, agreements and cooperation on the resilience of critical energy infrastructure must be nested within efforts towards greater energy security and, even one step further, towards the energy transition as a whole. While this perspective reveals the risks that poor critical infrastructure resilience may pose to the energy transition at large, it also highlights the potential for decision makers in this relatively new policy field to learn from the experiences made in other areas of the energy transition politics. One of these lessons learned is surely that all hands are needed on deck. Another is, however, that the concept of energy transition and also energy security has been constantly evolving and will likely continue to do so, adding tasks, shifting focus or direction of the work that needs doing and the composition of those hands most able to do it.

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7 In the German case, for example, it seems most inconvenient to claim NATO leadership in the Baltic Sea via the new Rostock headquarter on the one hand, and to have no coherent concept for a civil-military approach to the protection of critical maritime infrastructure on the other hand (as evident in the aforementioned parliamentary debate on a possible marine security law, see footnote no. 4).

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The Energy Innovation and Technology Tracker (EITT) - A Flashlight in the Complex Energy Innovation Landscape

By **Marlen Rein**

NATO operations and exercises bring together diverse technologies and equipment from multiple nations. Common goals, clear command structures and some occasional jokes help to integrate military personnel, build stronger teams and ease potential tensions. But what about the compatibility and interoperability of the equipment and energy technologies brought to the operations by the nations? In today's rapidly evolving and competitive innovation landscape, predominantly driven by the private sector, NATO forces use a wide variety of products and technologies. As a result, a single military camp may host multiple types of power systems, batteries, generators, energy management systems and other devices that are not always compatible with each other. Simply put, even the plugs and adapters might not match. Ambitious energy efficiency targets are pushing armed forces to innovate, explore alternatives to liquid carbon-based fuel and integrate more "outside-the-box" thinking. This evolving landscape presents both opportunities and challenges. While technological innovation is not only welcomed but also vital, NATO as an alliance must constantly strive to maintain interoperability and cohesion in energy related technologies.

Here, the **Energy Innovation and Technology Tracker (EITT)** comes in. The EITT is an informal tool that keeps a close eye on evolving energy-related innovations and technologies that could enhance NATO's military and technological advantage. Its goal is to highlight promising energy technologies or their components that could have a significant impact on the military's operational capabilities across the land, air and maritime domains, while promoting energy efficiency and interoperability across the Alliance. The EITT thereby serves as a "guiding light" to help nations navigate the complex innovation landscape. It also addresses the limitations and challenges related to the development, deployment or adaptation of these technologies for military purposes. Additionally, the EITT seeks to complement and support other existing initiatives, such as DIANA, the NATO Innovation Fund, the NATO Operational Energy Concept and others.

By **Marlen Rein**

Marlen Rein is a diplomat with the Ministry of Foreign Affairs of Estonia, currently serving as the Estonian Subject Matter Expert at the Research and Lessons Learned Division of NATO Energy Security Centre of Excellence (ENSEC COE), where she focuses on the linkage between energy security and cyber security, among other topics. Prior to joining the ENSEC COE, she was posted to the Embassy of Estonia in Madrid, dealing with bilateral political and economic relations. She also worked at the Permanent Representation of Estonia to the European Union, where she handled development cooperation and negotiations over the budget for EU external action, in addition to holding several positions at the Ministry. Before beginning her diplomatic career, she worked as a free-lance journalist for an Estonian daily newspaper. Ms Rein received her MA in East Asian Economy and Society from the University of Vienna in Austria.

Initiated by NATO Headquarters and developed in close cooperation with experts from different NATO entities, the International Energy Agency (IEA) and the NATO Energy Security Centre of Excellence (ENSEC COE), the EITT serves as an informative tool for military procurement entities as well as for officials from various government bodies working on energy efficiency and energy security. Currently, around 35 innovations and technologies have been identified as most relevant. These are divided into four categories: liquid fuels, hydrogen, electricity and energy storage and advanced propulsion systems. For each, the EITT provides brief information on its level of maturity, innovation trajectory, a general description and an explanation of its potential for military relevance. To objectively measure the maturity, the EITT relies on the Technology Readiness Level (TRL) provided by the IEA.

The EITT is a work in progress and will be updated regularly. Therefore, it also seeks feedback and suggestions from its active users. If you have any questions, comments, ideas for improvement or proposals for new technologies and emerging innovations to be added, we welcome your input. Please contact us at: eitt@enseccoe.org

HOW TO GET ACCESS?

https://www.enseccoe.org/eitt/

Since July 2025, the EITT is available on the ENSEC COE website. Access to the full EITT is granted to military and civilian personnel from Allied and NATO ENSEC COE contributing partner countries (registration required). Please note that an official military or government email address is required for registration.

We thank all the experts who contributed to the creation of the EITT. Special thanks go to Lukas Trakimavicius (NATO HQ) for his initiative and insightful ideas, and to Major Paulius Babilas (NATO ENSEC COE) for his invaluable technical support.

Future Operations - Resilience in Transitioning Energy: Power in Partnership: Civil-Military Synergy for Energy Security

By **Kristina Rimkūnaitė**

Each autumn, a diverse assembly of energy security experts from NATO nations and partner states - spanning military sectors, governmental bodies, academic institutions, and industry stakeholders - convenes at the annual NATO Energy Security Centre of Excellence FORTE conference. This pivotal gathering in Vilnius, Lithuania, organized by the NATO Energy Security Centre of Excellence serves as a catalyst for strategic dialogue and innovation, focusing on bolstering energy resilience amidst evolving geopolitical landscapes.

The presence of unidentified drones over Europe's critical energy infrastructure and airports, alongside hybrid and cyberattacks, disruptions in energy supply, electricity blackouts, and recent challenges to logistics and communications, underscores the paramount importance of energy security. This issue is of critical significance to both civilian and military sectors, necessitating a strong and coordinated response to protect vital national and international interests.

This year the conference emphasized three central themes: Operational Energy, which focused on optimizing energy resources within military operations; Military Infrastructure Resilience, outlining strategies to fortify infrastructures against energy disruptions; and valuable Lessons from Ukraine, offering insights into energy security challenges and strategies in kinetic conflict situations.

By **Kristina Rimkūnaitė**

Kristina Rimkūnaitė, FORTE 2025 organizer and Subject Matter Expert at NATO Energy Security Centre of Excellence.

Ms Kristina Rimkunaite is the representative of Lithuania at the NATO Energy Security Centre of Excellence's Research and Lessons Learned Division (NATO ENSEC COE RLLD) and a Diplomat at the Ministry of Foreign Affairs of Lithuania.

Ms Rimkunaite worked with extensive scope of many international energy projects from 2007 on. The sectors covered include oil, natural gas, shale gas, chemistry industries, and renewable energy systems (e-fuels, wind, hydro, solar, biomass, hydrogen).

Ms Rimkunaite is the leader behind the entire international "FORTE 2024" and "FORTE 2025" conference organization, making sure that you get to listen to the most interesting and experienced energy, security and defense experts that NATO and NATO nations have at the moment. In 2023, Ms Rimkunaite was unanimously acknowledged by 40 EU and EU candidate countries diplomats at the European Diplomatic Academy Pilot Project in Belgium as "Networker of the Year".

"FORTE 2025" brought together over 220 distinguished attendees. These three days were a confluence of thought leadership and expert insights, where keynote speakers and panelists engaged in comprehensive discussions covering an extensive array of topics. From pioneering innovations, such as advancements in solid hydrogen technologies, to the imperative protection of critical energy infrastructures, the conference provided a platform for in-depth exploration of critical issues.

During **"FORTE 2025"**, the exchange of expertise among NATO Headquarters and Agencies, NATO Centres of Excellence, the EU Joint Research Centre, and ministries of Defence, Transport, Communications, Energy, and Foreign Affairs from NATO member and partner nations, industry, as well as academic institutions such as the Naval Postgraduate School, significantly enhanced our collective capabilities. Such collaboration not only advances our strategic understanding, technology, policies, supply chains, and innovative practices related to energy security, but also provides a valuable platform for identifying partners for joint international initiatives within the defense sector. Furthermore, it fosters essential networking opportunities and ensures that we remain ahead of potential adversaries in both strategic and operational domains.

Complementing the rich dialogues, the conference facilitated an exhibition space where forward-thinking industrial representatives presented their cutting-edge services, production and energy supply solutions s. This provided an invaluable opportunity for demonstrating innovative solutions poised to enhance energy security and military capabilities.

For those interested in participating in the forthcoming "FORTE 2026" conference, which promises to continue this tradition of excellence and innovation in energy security discussions, inquiries can be directed to *forte@enseccoe.org*. Your engagement and contributions are vital in driving the civil-military synergy essential for future energy security resilience.

https://www.enseccoe.org/events/forte2025/

The organizers of **"FORTE 2025"** extend their sincere gratitude to all esteemed speakers, participants, partners, as well as representatives from academia and industry, for their invaluable contributions to the success of the conference.

Photo by Major Paulius Babilas (NATO ENSEC COE)

Modelling Liquid Fuel Futures for Defence: Exploring the Role of Biofuels in European Supply Security with the new Biofuel Calculator

By **Ben Cook**

While many civil societies in industrialised countries move toward electrification, several sectors remain hard to electrify due to constraints such as high energy-density requirements, long-range operational demands, and limited technological alternatives. Aviation, maritime shipping, and defence are likely to rely on liquid fuels for decades to come. [1]

For these sectors, the central issue is the future availability and resilience of liquid fuel supply. Oil refineries processing fossil crude, particularly in Europe, are under pressure from lower-cost global competitors and, consequently, closures appear likely. [2] For sectors still reliant on liquid fuels, this could mean longer, more vulnerable supply chains. This will pose a strategic risk to the assurance of fuel supply in the European theatre.

To address this requirement, the NATO Energy Security Centre of Excellence (ENSEC COE), in cooperation with partners from NATO, industry, and academia, has developed the Biofuel Calculator, a quantitative modelling tool designed to assess biofuel supply potential across the European theatre. It provides a view of the availability of drop-in replacements for jet fuel, diesel, and gasoline out to 2050 under different scenarios. The tool contributes to holistic assessments of supply security of military fuel demand and highlights interactions with civil sectors.

The model is underpinned by long-term EU projections of sustainable biomass availability. These feedstock volumes are translated into estimates of liquid fuel output using pathway-specific conversion factors. It incorporates key technical parameters, including feedstock energy content, conversion efficiencies, and process yields. It captures current and announced biofuel production capacity across Europe and enables a gap analysis between existing capacity and projected fuel availability requirements. Users can adjust the share of biomass allocated to liquid fuel production, with assumptions informed by national policy objectives and commercial viability of individual conversion pathways.

The development of the **Biofuel Calculator** tool will continue, with future iterations informed by user feedback, expanded scenario analysis, and ongoing methodological refinement. A full policy paper will be prepared to capture findings and implications. The ENSEC COE invites defence planners and policymakers to test the tool and contribute national perspectives. Industry and researchers are also encouraged to share data, validate assumptions, and join upcoming workshops and demonstrations.

The objective is to help defence planners identify bottlenecks and assess whether domestic or Allied biofuel production could close emerging gaps. Where shortfalls are projected, the tool can support policy development to protect energy resilience, such as targeted investment in production capacity.

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[2] IEA, "World Energy Outlook 2024," Paris, 2024.

By **Ben Cook**

Ben Cook is the UK Representative at the NATO Energy Security Centre of Excellence, where he is on secondment from the UK's Department for Energy Security & Net Zero (DESNZ). Ben's work explores future demand and supply of energy to NATO nations and operations, and the interactions between civil and defence sectors. Previously, Ben was Head of Future of the Gas System at DESNZ, where he developed the Future of Gas Programme and led several gas supply security projects in the wake of Russia's full-scale invasion of Ukraine.

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