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POWERBASE

D2.5 SOTA report & actors map v2

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About the document

The "SOTA Report and Actors Maps V2" presents the methodology and findings of Task 2.3, titled “State of the Art (SOTA) Review: Research and Existing Solutions.” And Task 2.4 “Capability Gap Validation”. This document includes concise technology fact sheets that detail technical performance, functionality, and preliminary evaluation of basic requirements, such as logistics. Each fact sheet offers a snapshot of technologies relevant to a low-emission energy supply system, primarily focusing on commercial off-the-shelf solutions, while also highlighting emerging solutions in research and development. Additionally, they provide the results of an overview of relevant suppliers and their products or research and technology organizations for the specific technologies. The report further incorporates a patent analysis, identifying key patent holders and technological maturity trends, which helps to identify innovation activity and highlight potential future developments. It also presents the results of a supplier survey conducted among technology providers, offering insights into the availability, scalability, and compliance of current solutions with end-user requirements. Finally, the document includes a matching between the requirements defined by end-users in D2.3 and the performance indicators of the reviewed technologies, enabling an evidence-based assessment of their suitability and gaps with respect to operational needs.

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This document includes contributions such as technologies proposed by project partners, along with external inputs from parties who have provided additional solutions for data collection and supplier mapping.

Nature of the deliverable **Report**

Dissemination level

PU	Public, fully open. e.g., website	**x**

Copyright notice

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Abbreviations

AC	Alternating Current
AEM	Anion Exchange Membrane
AFC	Alkaline Fuel Cell
AI	Artificial Intelligence
ARTTIC	ARTTIC Innovation GmbH
AutRC	Austrian Red Cross
BoO	Bases of Operation
CdTe	Cadmium telluride
cGH_2	Compressed Gaseous Hydrogen
CHP	Combined Heat and Power
CIGS	Copper–indium–gallium–selenide
COTS	Commercial Off-The-Shelf
CPC	Cooperative Patent Classification
C-Si	Crystalline Silicon
db	Decibel
DBT	Dibenzyltoluene
DC	Direct Current
DOE	Department of Energy
EDLC	Electric double-layer capacitance
E-Fuels	Electrofuels
EHPET(s)	Emerging Highly Promising Emerging Technologies
ELPET(s)	Emerging Lowly Promising Emerging Technologies
EMPET(s)	Emerging Moderately Promising Emerging Technologies
ERO(S)	Emergency Response Organization
ES(s)	Emergency Shelter
EU	European Union
GDPR	General Data Protection Regulation
HAWT	Horizontal-axis wind turbines
Hz	Hertz
ICE	Internal Combustion Engines
IoT	Internet-of-Things
IEA	International Energy Agency
IPC	International Patent Classification
IRENA	International Renewable Energy Agency
J	Joule
JRC	Joint Research Centre
KEMEA	Center for Security Studies
LCoE	Levelised Cost of Energy
LDR	Lift to drag ratio
LFP	Lithium Iron Phosphate
LH_2	Liquid Hydrogen
Li-S	Lithium-Sulphur
LISICON	Lithium Super Ionic Conductor
LLZO	Lithium lanthanum zirconate
LMO	Lithium Manganese Oxide
LOHC	Liquid Organic Hydrogen Carrier
LPoE	Levelised Profit of Energy
M	Project Month
MeH	Metal hydrides
MCFC	Molten Carbonate Fuel Cell
MCH	Methylcyclohexane
MGT	Micro Gas Turbine
MPPT	Maximum Power Point Tracking
MSB	Swedish Civil Contingencies Agency
NASICON	Sodium Super Ionic Conductor
NCA	Nickel Cobalt Aluminium Oxide
NMC	Nickel Manganese Cobalt Oxide

OMC	Open Market Consultation
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PNO	PNO Consultants
P2P	Power-to-Power
PCP	Pre-Commercial Procurement
PERO(S)	POWERBASE Emergency Response Organization
PtL	Power-to-liquid
PV	Photo-voltaic
RFI	Request-for-Information
SHG	Small Hydro Generators
SOECs	Solid Oxide Electrolysis Cells
SOFC	Solid Oxide Fuel Cell
SOTA	State of the Art
SPEs	Solid Polymer Electrolytes
SSB	Solid State Battery
SSFS(s)	System Solution Fact Sheet
SWT	Small Wind Turbine
T	Task
TCO	Transparent conducting oxide
TED	Tenders Electronic Daily
TFPV	Thin-film photovoltaic
TFS(s)	Technology Fact Sheet
THW	Federal Agency for Technical Relief
V	Volt
VAWT	Vertical-axis wind turbine
W	Watt
Wh	Watt hours
WP	Work Package
WS	Workshop
WtE	Waste-to-Energy

Executive Summary

This deliverable presents the final phase of Task 2.3 "*State of the Art (SOTA) Review: Research and Existing Solutions*" within the POWERBASE project, focusing on the identification, evaluation, and comparative analysis of alternative low-emission power solutions for emergency shelters and operational bases of European emergency response organizations. The report provides a systematic assessment of both commercial-off-the-shelf technologies and emerging technologies, creating a robust foundation for comparing their performance metrics, operational feasibility, and potential deployment in emergency response scenarios.

By synthesising insights from extensive literature reviews, a structured patent analysis and an analysis of the publication dynamics, this study has developed detailed technology fact sheets. These fact sheets describe technical performance, functionality, and logistical considerations, while also identifying relevant suppliers, research organizations, and innovation activities through bibliometric and patent data. The supplier survey provides complementary insights into the maturity and compliance of existing solutions, further grounding the assessment in real-world market perspectives.

A key addition of this deliverable is the matching of end-user requirements, as defined in Deliverable D2.3, with the performance indicators of the reviewed technologies. This enables a capability gap analysis, highlighting where current solutions already align with operational needs and where further development or innovation is required.

These consolidated findings provide also the final results of Task 2.4 "*Capability Gap Validation (SOTA vs. requirements)*". By integrating technology evaluation, patent landscapes, supplier insights, and requirement matching, this deliverable strengthens the strategic foundation for future PCP activities and supports informed decision-making for the transition towards sustainable, low-emission energy supply in emergency response operations.

1. Introduction

1.1. SOTA and Actor mapping in the context of POWERBASE

In the context of the broader POWERBASE project, as outlined in the Grant Agreement, the State-of-the-Art (SOTA) Analysis and Stakeholder Mapping represent a vital component, specifically detailed in T2.3 "*State of the Art (SOTA) Review: Research and Existing Solutions*" Together with Task 2.4 "*Capability Gap Validation (SOTA vs. requirements)*", these activities have now been completed within the project timeframe from M2 to M12.

The primary objective was to identify and analyse solutions designed to reduce emissions and potentially substitute diesel generators by evaluating existing and emerging technologies for power supply in Emergency Shelters (ES) and Bases of Operations (BoOs). Furthermore, the tasks catalogued the key stakeholders involved in the supply and development of such potential solutions, while systematically validating their alignment with end-user requirements.

Building on the preliminary results presented in Deliverable D2.4 "*SOTA Report & Actors Map V1*" (submitted in M5), this final deliverable (D2.5) consolidates and refines the findings. To enhance usability for end-users, the technology fact sheets have been streamlined and presented in a more concise and reader-friendly format. In addition, a structured patent analysis has been incorporated to provide a clearer picture of supplier activities and innovation trends.

During August 2025, a dedicated supplier survey was carried out to capture the availability, scalability, and operational maturity of relevant solutions. The survey was explicitly structured around the requirements defined by end-users in Deliverable D2.3, allowing a systematic assessment of the extent to which current products already meet operational needs. Based on this, the requirements and product functionalities were matched to identify existing capability gaps.

This process enables a transparent, evidence-based foundation for decision-making in the preparation of Pre-Commercial Procurement (PCP). By combining technology evaluation, patent analysis, publication dynamics, supplier insights, and requirement matching, Deliverable D2.5 provides the final results of Tasks 2.3 and 2.4, delivering a comprehensive basis for subsequent procurement steps and informed strategic planning.

1.2. Definition of SOTA-Analysis

Although a substantial body of literature exists on SOTA-analyses, there is no unified definition or standardised methodology. Within POWERBASE, a SOTA is defined as a structured synthesis of the most advanced developments in a given technology domain. It systematically reviews and evaluates recent research, innovations, and practices to identify benchmarks, strengths and limitations, and emerging trends. This approach aligns with the six-step framework by [1], which emphasises that SOTAs are not just descriptive but interpretive syntheses, highlighting evolution, gaps, and future directions.

The SOTA in POWERBASE serves to inform practitioners, procurers, and decision-makers about technological advancements and to prepare procurement by mapping key stakeholders, from commercial suppliers to research organizations. A detailed description of the applied SOTA methodology is provided in Deliverable D2.4. Building on this, the current deliverable extends the analysis by integrating patent data, supplier feedback, and requirement matching, with a focus on mobile, low-emission electricity solutions for ESs and BoOs.

1.3. Analysing Components: Energy generation, conversion and storage

In emergency response operations the difference between having or lacking dependable power often determines the safety and effectiveness of response. POWERBASE positions mobile, low-emission micro-power systems for Emergency Response Organizations (EROs) to replace or complement diesel sets. Within this context, three foundational concepts, energy generation, energy conversion, and energy storage, structure how technologies are selected and integrated for resilient field power.

Technical Note:

Energy is the capacity to do work or produce heat; it accumulates over time and is measured in joules (J) or kilowatt-hours (kWh). **Power** is the rate at which energy is generated, converted, or consumed; it is measured in watts (W), where 1 W = 1 $J \cdot s^{-1}$.
For sources and storage, distinguish power capacity (kW: how fast energy can be delivered) from energy capacity (kWh: how much total can be delivered).

In microgrids, PV or generators provide power (kW) at any moment, batteries store energy (kWh), and power electronics convert form/voltage — losses in conversion reduce the energy ultimately delivered.

Energy generation:
Energy generation (in electricity contexts, "power generation") is the production of electrical power from primary energy; for example, sunlight, wind, flowing water, chemical fuels, geothermal heat, or nuclear fission (see Figure 1).

"Power generation is defined as the process of converting energy from one form to another to produce electricity, utilising methods such as thermal, hydro, and nuclear systems." [2]
"An electric generator is a device that converts a form of energy into electricity." [3]

In practice, most generation devices use a conversion step (e.g., a heat engine driving a generator, a PV module turning photons directly into DC electricity, or a fuel cell turning chemical energy to electricity). The defining feature is that generation adds net energy to the local system boundary by drawing on a primary source. Typical technologies include portable photovoltaic (PV) arrays and solar trailers; compact wind turbines; engine-generator sets (diesel, natural gas); hydrogen fuel cells; and microturbines.

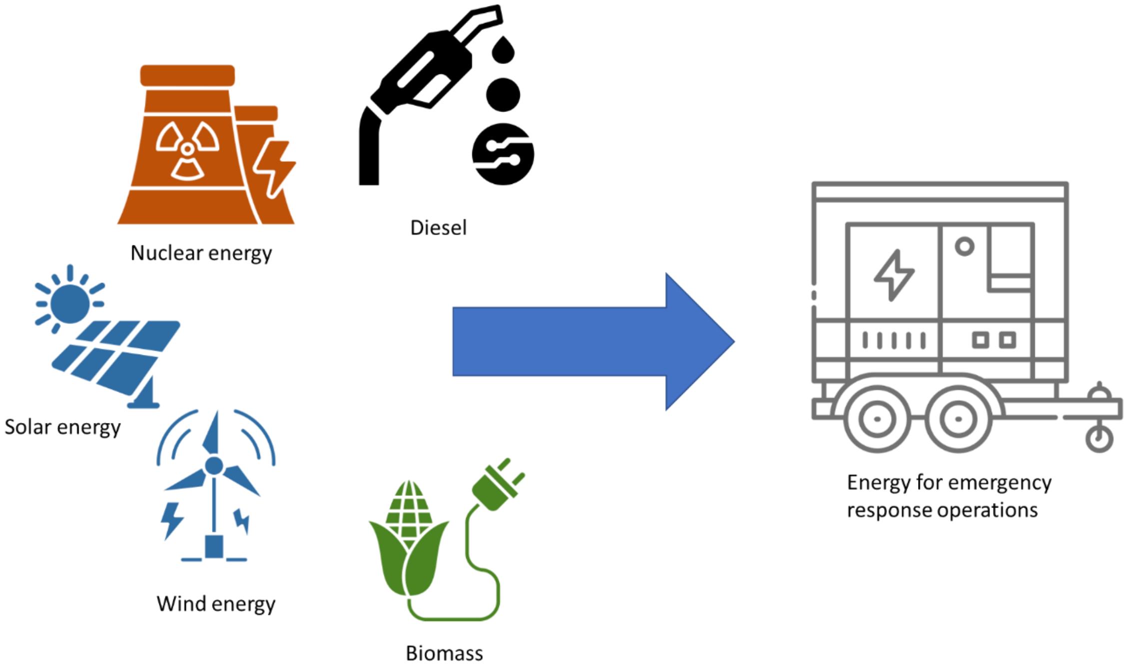

Figure 1: Different theoretical types of energy generation.

Energy conversion:
Energy conversion is the transformation of energy from one form to another (mechanical <-> electrical, chemical <-> electrical, thermal <-> mechanical, etc.).

- *"Energy conversion refers to the process of changing energy from one form to another, while adhering to the principle of conservation of energy, which states that the total amount of energy remains constant during such conversions." [4]*
- *"Energy conversion, the transformation of energy from forms provided by nature to forms that can be used by humans" [5]*
- *"In technology, energy conversion generally refers to operations in which energy is made more usable; for instance, in the burning of fossil fuels to convert chemical energy into electricity. Among the forms of energy that can be converted are chemical, atomic, electrical, mechanical, light, potential, pressure, kinetic, and heat energy." [6]*

Energy conversion is most generally the transformation of energy from one form to another; for example, chemical → electrical, electrical → mechanical, or thermal → mechanical (see Figure 2). This broad, physics/engineering definition appears across scholarly and educational references (e.g., 4,6,7). In this view, conversion is bidirectional wherever physics permits: the same pair of technologies can often run "forward" or "reverse" (motor <-> generator, electrolyser <-> fuel cell), and electricity can be converted onward to other useful forms such as hydrogen (via electrolysis), light (LEDs), or heat (resistive heaters, heat pumps).
A second, more resource-to-service framing, common in energy-systems overviews (e.g., [5]), emphasises transformations from forms provided by nature to forms useful to humans. Typical examples are sunlight or wind → electricity, or chemical energy in fuels → mechanical work and then electricity via generators. This perspective is helpful when mapping primary resources to end-use energy, but it can obscure the equally important "reverse" or lateral conversions inside engineered systems (electricity → hydrogen for storage and later reconversion, electricity → photons for lighting and signalling).
Within POWERBASE we will use the general definition: "the transformation of energy from one form to another". An important aspect is: Conversion does not create energy; it changes form while obeying conservation of energy. What matters for design is efficiency (fraction delivered in the target form).

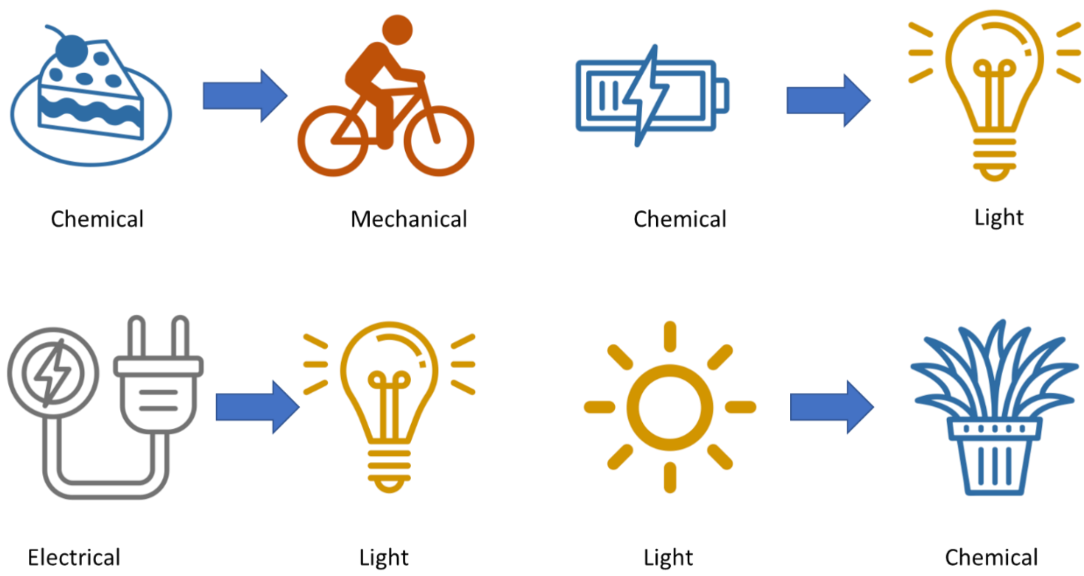

Figure 2: Different types of energy conversion

Electrical power conversion is the deliberate adapting and shaping of electrical power so that sources, storage, and loads work together safely and efficiently. Using power electronics (and some passive parts), the system adjusts voltage, current, frequency, phase, and waveform to what the equipment needs (see Figure 3).
In practice this includes:

- DC <-> AC: inverters and rectifiers (e.g., battery/PV DC to 230 V, 50 Hz AC; or AC back to DC for charging).
- DC <-> DC: converters that step voltage down or up and control current to match devices and battery buses.
- AC <-> AC: changing voltage or frequency between different AC standards.
- Regulation & isolation: transformers and regulators that stabilise voltage and provide electrical isolation for safety and power quality.

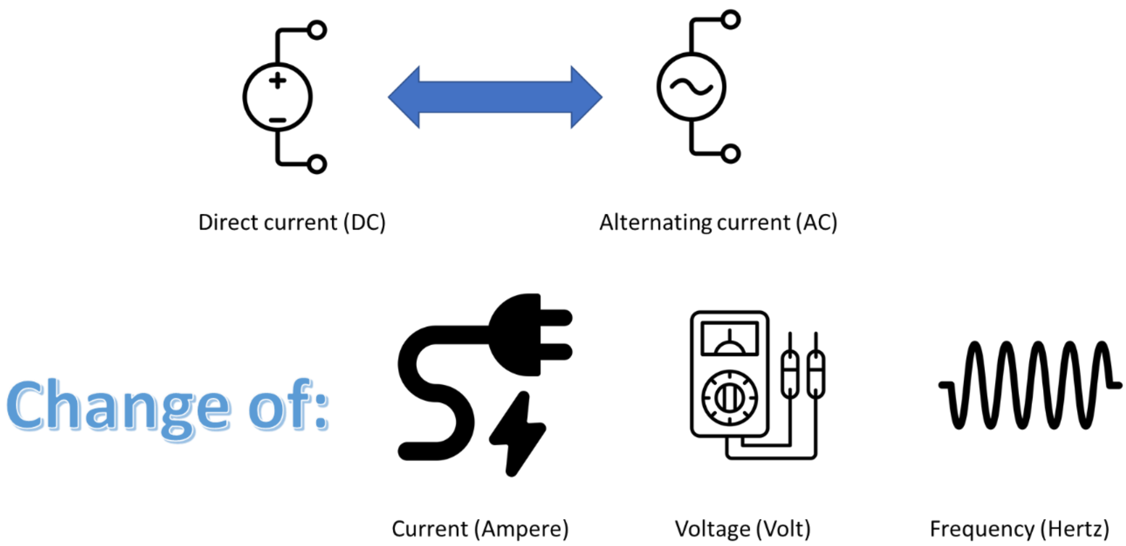

Figure 3: Different electrical power conversions

Overall, we have two types of conversions: the resource-to-usable conversions, for example, turning a PV array's DC output into grid-compatible AC, and internal "matching" conversions within the power unit, where the source is tailored to exactly what a load requires. Additionally, there are broader energy conversions across domains which includes converting electricity into hydrogen with an electrolyser for later use, ensuring safe, efficient operation across all connected devices.

Energy storage:
Energy storage captures energy now for use later, balancing variable supply and changing demand. In mobile emergency power, storage keeps critical devices on during brief outages (ride-through), trims short load spikes (peak shaving), can start a microgrid from zero (black start), and improves power quality (stable voltage/frequency). It also enables “silent hours” with generators off.
Common classes by stored form: Electrochemical (e.g. lithium-ion batteries) as the workhorse for hours of supply. Electrical (e.g. supercapacitors) for very fast bursts (seconds). Mechanical (e.g. flywheels) for short, high power; larger stationary options include pumped hydro or compressed/liquid air for long duration. Thermal (e.g. hot-water tanks and phase-change materials) store heat or cold for later use; converting this back to electricity requires an additional conversion step. Chemical carriers (e.g. hydrogen) made by electrolysis stores energy for days to months and is reconverted via fuel cells (see Figure 4).

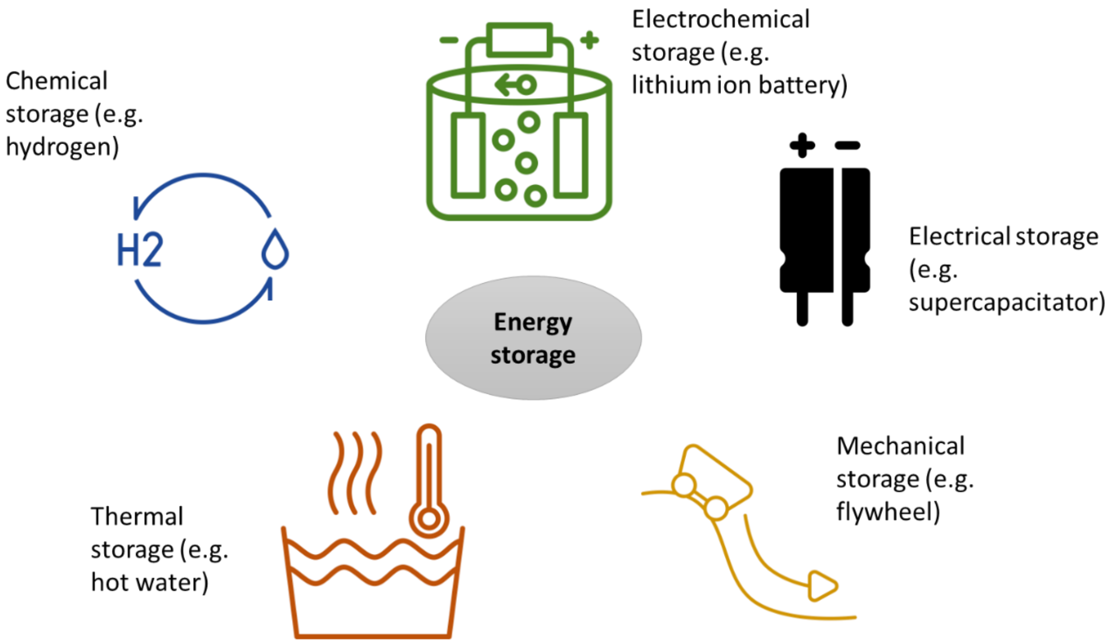

Figure 4: Different forms of energy storage.

Here’s a process description (see Figure 5) that ties together the three functions used in POWERBASE (generation, conversion, and storage) for an emergency shelter or base of operations:

Step 1 — **Energy generation from renewables.**
For example, portable photovoltaics (PV) or suitable, small wind or clean fuel cells provide the primary energy. PV produces DC electricity that varies with sunlight; fuel cells provide steady DC when fuel is available. In addition, conventional fuel-based generators, such as diesel or other commercially available fuels, may also serve as primary energy sources, either as a backup option or as part of hybrid system configurations.
Step 2 — **Energy conversion for immediate use or storage.**
As power is generated, it is conditioned by power electronics to ensure safe and reliable use in the shelter. In the direct-use path, for example, electricity from photovoltaics is converted from fluctuating DC into stable 230 V AC to operate radios, lighting, IT equipment, or medical refrigerators. In the storage path, excess electricity is directed to the battery system, where it is stored for later use. The same inverter/charger ensures safe charging and protects both the batteries and connected devices.

Step 3 — **Supply during non-generation periods.**
When generation is low or unavailable (e.g., at night for PV), the battery energy storage system discharges and the inverter/charger convert that DC back to the required AC/DC for the shelter. This covers night operations and enables quiet hours with the generator off, while maintaining power quality (stable voltage and frequency) and supporting black-start if needed.
Optional surplus-to-fuel conversion.
When there is excess renewable power, energy conversion can also produce chemical energy for long-duration storage or later use elsewhere, for example, driving an electrolyser to make hydrogen. That hydrogen can be transported or stored and later reconverted to electricity with a fuel cell, extending autonomy and improving logistics.

In practice, a small islandable microgrid controller coordinates these flows, prioritising direct use, topping up storage, shifting to discharge when needed, and engaging surplus-to-fuel only when conditions are right, so the shelter remains powered, low-emission, and resilient.

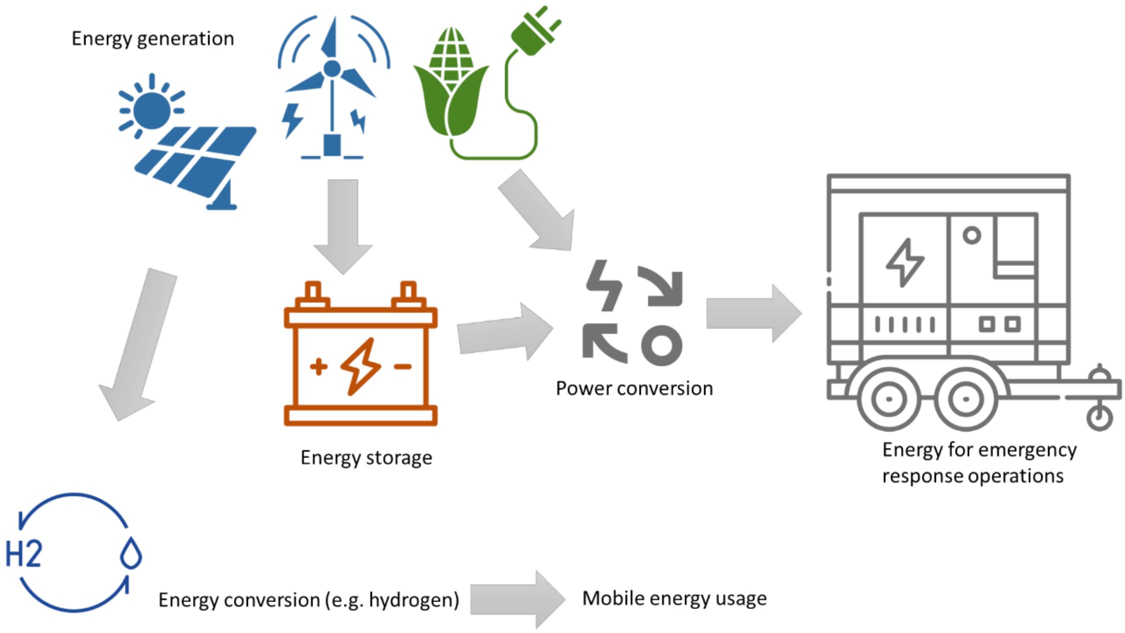

Figure 5: POWERBASE process of energy generation, storage and conversion.

2. Methodology and procedure

2.1. Overview of the methodology

To support evidence-based procurement preparation, we conducted a structured State-of-the-Art (SOTA) analysis to identify, evaluate, and validate mobile low-emission power solutions for Emergency Shelters (ESs) and Bases of Operations (BoOs), ensuring their alignment with the operational requirements of European Emergency Response Organizations (EROs)." Methodologically we followed a six-step pathway based on [1]

- **Define scope & questions** – focus on mobile low-emission power solutions for BoOs and ESs.
- **Set timeframe** – assess current solutions and emerging options up to 2035.
- **Refine questions** – concentrate on electricity generation, conversion, and storage (excluding heating/cooling and demand-side measures).
- **Systematic search strategy** – combine practitioner input, research project results, literature reviews, and partner contributions.
- **Comprehensive analysis** – review literature and product data, evaluate feasibility, maturity, and market status, and develop technology fact sheets (TFS).
- **Validation & gap identification** – align findings with ERO needs, identify gaps, and prioritise technologies for further investigation.

The full methodological description and detailed results of steps 1–5 are presented in Deliverable D2.4, while Deliverable D2.5 builds on these foundations with final validation results and capability gap analysis (T2.4).

2.2. Solution identification

This chapter explains the methodology used to search for and progressively identify technologies relevant to the POWERBASE project. It covers Stage 4 ("Developing a systematic search strategy and identifying solutions and related information") and Stage 5 ("Conducting a Comprehensive Analysis"), detailing how the identified technologies were categorised and subsequently organised for further examination.

2.2.1. Initial solution collection

The initial collection for identifying suitable solution for POWERBASE was based on four different sources:

a) Practitioner-driven input

To ensure practical relevance, practitioner input from Emergency Response Organizations (EROs) was integrated from the start. THW experts contributed early insights during the proposal phase, helping to identify potential technologies. At the Kick-Off Meeting, PEROs highlighted further solutions, such as AutRC's photovoltaic "Sunflowers" and MSB's renewable energy systems for shelters in Africa. During WS2, discussions on operational requirements expanded the range of options, including PV panels, batteries, solar tents, electric vehicles, seawater batteries, printable units, and methane-based storage. These contributions ensured that scenario and requirements workshops not only defined needs but also pointed to promising technological solutions.

b) **Research projects in the area of renewable energies (especially mobile solutions)**
Several projects in the field of renewable energies, particularly focusing on mobile solutions, have been identified. These include, for example, REMULES[1] (KIRAS), NOMAD[2], Suninbox, [3]CHeaP[4], Schneeberger[5], REACH[6], RenGen[7], MobileBattery[8], SophiA[9], and H2Rescue[10]. These projects also describe the underlying technologies for the generation, conversion, and storage of renewable energy.

Particularly relevant for the SOTA-analysis is the recently completed INDY[11] project, which developed technology briefs for a comparable focus area (military camps). The identified projects, and especially INDY, have served as one of the key pillars for identifying the list of technologies considered in POWERBASE.

c) **Publications of Global Renewable Energy Research Institutions**
For a more structured and systematic analysis, a literature review was conducted to examine scientific sources summarising key developments in the green energy transition, as well as outlooks and roadmaps for relevant technologies. This review includes sources from the International Energy Agency (IEA) [8–10], the International Renewable Energy Agency (IRENA) [11–13], the European Commission’s Joint Research Centre (JRC) [14] and Fraunhofer [15–17]. Similar to the examination of different project results, the study assessed the technologies, based on the mobility and electricity supply focus.

d) **Additional Datasheet from partners and contacts**
Additionally, we created a database to gather information from individuals who contacted us via our website or LinkedIn regarding relevant technologies and complete technology systems. The database was also accessible to all Powerbase partners throughout the project, allowing them to add relevant products they discovered. Entries were assessed and categorised by technology components or systems.

Building on these identified technologies from the other research projects, publications from global renewable energy research institutions and the additional Datasheet, an initial list of technologies was compiled.

2.2.2. Basic requirements identification

A key challenge for T2.3 arose from the tight 12-month project timeline, which required the State-of-the-Art (SOTA) analysis to run in parallel with the definition of end-user requirements. While preliminary assumptions were made early on, the requirements of the Emergency Response Organizations (EROs) were systematically identified through workshops and surveys. The final, consolidated version of these requirements was published in Deliverable D2.3 “End-User Requirements.”

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[1] https://www.kiras.at/gefoerderte-projekte/detail/remules/
[2] https://www.projectnomad.eu/
[3] http://www.suninbox.eu/
[4] https://cordis.europa.eu/project/id/684516
[5] https://cordis.europa.eu/project/id/882564
[6] https://cordis.europa.eu/project/id/830204
[7] https://cordis.europa.eu/project/id/763365
[8] https://cordis.europa.eu/project/id/666278
[9] https://cordis.europa.eu/project/id/101036836
[10] https://www.dhs.gov/science-and-technology/news/2023/08/17/feature-article-using-hydrogen-power-disaster-relief
[11] https://ife.no/en/project/indy-energy-independent-and-efficient-deployable-military-camps/

The requirements were structured into the following categories:

- Functionality
- Efficiency
- Performance
- Scalability
- Interoperability
- Components to be fed (specific)
- Resistance
- Availability / Maintenance
- Applicability / Staff Handling
- Safety & Security
- Logistics / Transportation
- Sustainability / Multi-Use
- Standards / Procedures
- Financial Aspects
- Potential solution approaches

These categories served as the basis for aligning the identified technologies with operational needs, guiding the development of Technology Fact Sheets (TFSs), and ensuring relevance for subsequent capability gap analysis and procurement preparation.

2.2.3. Literature review

The process combined a literature review (Web of Science, Springer Nature, Google Scholar) and targeted keyword searches covering the past three to five years to ensure up-to-date insights. Publications were analysed to understand functionality, advantages and disadvantages, and to identify challenges and ongoing research (see Figure 6).

In parallel, market studies and industry reports were reviewed to assess commercialization potential, adoption, and key suppliers. Integrating scientific findings with market data provided a well-rounded view of technological progress and economic relevance. This structured approach enabled systematic filtering and prioritization of relevant technologies, laid the groundwork for their presentation to EROs in WS4, and supported the development of the Technology Fact Sheets.

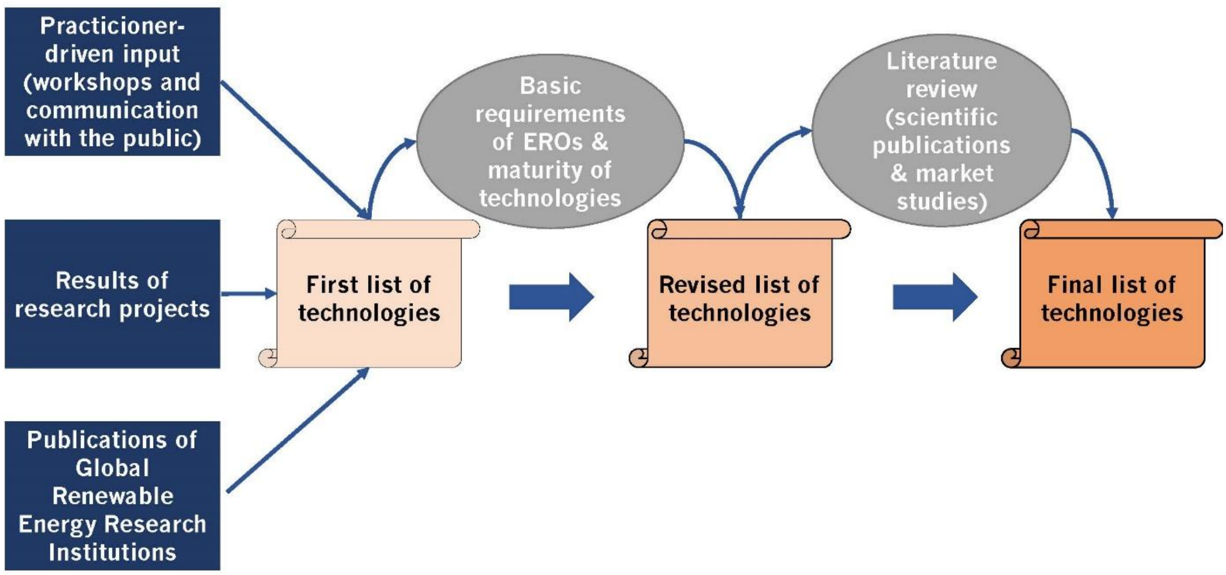


Figure 6: Methodology to identify the list of technologies for POWERBASE

Based on this analysis, the technologies were broadly classified into four categories (see Table 1). For the first two categories, comprehensive technology briefs were developed, while for the latter two, concise mini-briefs were created:

- Commercial Off-The-Shelf (COTS) promising technologies
- Emerging highly promising technologies (EHPET)
- Emerging moderately promising technologies (EMHPET)
- Emerging lowly promising technologies (ELPET)

Table 1: Final list of Technologies

COTS technologies	Emerging highly promising technologies (EHPET)	Emerging moderately promising technologies-(EMHPET)	Emerging lowly promising technologies (ELPET)
Crystalline Silicon Solar Cells	Wave-energy converters	Perovskite and tandem solar cell	Small modular nuclear reactors
Thin Film Panels (second generation)	Sodium-Ion Batteries	Airborne wind & kites	Tidal Energy Generators
Small -Hydro Generators	Metal Hydrides for Hydrogen Storage	Solid-state wind energy technologies	Pedal-Powered Generators
Small Wind Turbines	Solid-state batteries	Lithium Sulphur batteries	Liquid organic hydrogen carriers
Lithium-Ion Batteries		Metal-Air Batteries	E-Fuels
Hydrogen Storage		Hydrogen internal combustion engines	E-Ammonia
Flow-batteries		Methanol	Methanol
Hydrogen Fuel cells			Compressed Air Energy Storage (CAES)
Electrolysers Hydrogen			Super capacitators
Micro gas turbines (MGTs			Carnot Batteries (CB
Biomass and waste to Biogas			Flywheel (mechanical energy storage)
Methanol-based energy systems			

2.3. Structure of the Solution Catalogue (technology fact sheets)

Chapter 3 presents the Technology Fact Sheets (TFSs), each evaluating an individual technology relevant to low-emission energy supply systems for BoOs and ESs. For example, a solar panel qualifies as an individual technology because it generates intermittent electricity and requires complementary storage and conversion solutions.

For each of the COTS technologies and emerging highly promising technologies (EHPETs), a full TFS has been developed. For the remaining emerging technologies (EMPETs and ELPETs), Mini-technology fact sheets have been created, providing a concise summary of their functionality, as well as their key advantages and disadvantages.

The rationale for distinguishing between full and Mini-TFSs is that POWERBASE prioritises COTS technologies and EHPETs, because these solutions require significantly less effort to adapt to emergency response scenarios and their unique requirements.

In response to end-user requests, the TFSs have been shortened in comparison to their first version in D2.4 to provide a more accessible and reader-friendly overview. Each fact sheet now includes:

- **Technology Functionality** – Provides a concise but technically sound description of how the technology works and what it delivers (e.g. power generation, storage, conversion). This section establishes the core principle and key performance features so that later matching with end-user requirements is straightforward.
- **State of the Art and Market Analysis** – Summarises the current development stage, technical maturity, recent innovations, and market trends. This includes cost developments and patent/publication activity to indicate whether the technology is commercially available, emerging, or still experimental.
- **Stakeholders and Actors** – Identifies the main industrial players and research organisations active in developing or supplying the technology. This section gives and overview of the top global market leaders derived from market studies and the project's own patent analysis. This section presents also example products from market leaders and other representative solutions, including options available on the European market or products that illustrate the range of configurations and those that appear particularly suitable for disaster and emergency management.
- **Practical Implications for End-Users** – Translates the technical and market findings into operational relevance. It outlines deployment conditions, logistics, maintenance needs, training requirements, and safety considerations to help emergency response organisations assess feasibility in real-world missions.

This streamlined format ensures that practitioners can quickly grasp the potential and limitations of each technology while maintaining the necessary detail for capability gap analysis.

For emerging technologies that have not been classified as the most promising technologies due to a lack of market proximity or incompatibility with the requirements of PEROs, Mini-TFSs have been created. These fact sheets only include two sections: Functionality and Technical Explanation, as well as an overview of the advantages and disadvantages of the respective technology and the expected relevance for EROs.

As already described in Chapter 1, emergency response organizations generally require an integrated system composed of multiple components such as energy generation, storage, and conversion.
Several systems that combine two or more of these components are already available on the market, although they are not yet specifically tailored to the operational requirements of Emergency Shelters and Bases of Operation. In Chapter 4 and 5, we present selected examples of such multi-component systems to illustrate current market offerings and their potential for adaptation to emergency response needs.

2.4. Patent Analysis

To complement the State-of-the-Art (SOTA) analysis, a patent analysis was carried out to map key suppliers and research and technology organisations (RTOs) and to understand how actively each technology is being developed worldwide and within Europe. Beyond identifying the most advanced technological solutions, the goal was to show which actors (commercial companies as well as RTOs) are driving innovation, how strong Europe's position is, and whether the technology is still in an intensive research phase or already reaching maturity.

The methodological approach applied to each technology combined keyword-based searches and iterative refinement. Initially, **keywords** were identified based on previous results, and a preliminary search query was constructed in Patbase (one of the leading patent databases) to find relevant patents for the respective technology that would serve as the basis for the analysis. Subsequently, **the IPC and CPC classes** in the results were inspected to ensure that the search query was precise and targeted. If necessary, the search query was adjusted, including by narrowing down the classes to increase the relevance of the results. In the next step, the search results were evaluated in bullet points. Special attention was paid to abbreviations and general terms that could potentially affect the quality of the results. This evaluation was repeated several times until the search results matched the technology sought. To further enhance relevance, the results were restricted to **active patents** (patents whose rights are active), which helped to consider only the most current and relevant information. Another important aspect of the methodology was the extraction of the **main patent holders or applicants** of the patent families (multiple patents related to the same invention are grouped under families). This enabled the identification of the central players in this field. To obtain a more comprehensive picture, the main offices of the applicants were identified at the country and continent level. The results were then visualised using R to provide a clear representation of the data. Finally, a search for publications was conducted with a slightly modified search query, retaining only the relevant keywords. In assessing the results, it can be said that a large number of patents and publications indicate that the topic has been or is being intensively researched. A declining publication dynamic further suggests that the technology has reached a high level of maturity and is no longer primarily addressed in scientific discourse.

The patent analysis delivers the following key outputs for each technology:

- **Top patent families** – a ranking of the leading patent families by applicant, including the country of origin, with continents (Asia, Europe, North America) colour-highlighted for quick geographic comparison.
- **European focus** – a separate diagram showing the same ranking restricted to European applicants only.
- **Market leaders** – identification of the five global market leaders and a list of significant European companies active in the field.
- **Publication dynamics** – a timeline graph illustrating scientific publication activity, indicating whether the technology is still heavily researched or has passed its peak and reached a higher maturity level.

These combined insights reveal not only the technological landscape but also the strength and regional distribution of innovation actors, supporting evidence-based decisions for procurement and future research investments.

2.5. Supplier Survey

From 6 to 22 August 2025, a supplier survey was conducted to assess the availability and maturity of sustainable, low-emission, and compact energy supply technologies that could serve as alternatives to diesel generators in emergency response and field operations.

For the supplier survey the consortium relied on the supplier contact base established during the Open Market Consultation (OMC) activities. As described in Deliverable D3.2, a comprehensive list of technology providers was compiled during the preparation and execution of the OMC workshops and technology showcases.

Suppliers were invited to register through the POWERBASE website following the publication of the Prior Information Notice on TED and the OMC scope document. Contact details were collected in compliance with GDPR and used to disseminate information about the OMC events, the Request for Information (RFI) questionnaire, and related activities.

The resulting database, comprising companies that had expressed interest in the project and/or participated in OMC events, served as the primary source of contact addresses for the supplier survey. In addition to the OMC supplier list, further contacts were added through the market research carried out for the preparation of the technology fact sheets. This supplementary research identified market leaders and other relevant actors in the renewable energy and energy-storage sectors, whose contact details were integrated into the survey mailing list to ensure a broader and more representative coverage of the market.

The survey instrument was based on the technical and functional requirements defined in the Emergency Response Organisation (ERO) analysis and documented in Deliverable 2.3. The survey is based on 14 main requirement categories, many of which include additional sub-categories and a Supportive/Additional Statement on "Functional / Performance Requirement":

1. The system **generates electrical energy from renewable** or renewable-based sources (e.g., solar, wind, bio-based, or hybrid combinations) in proximity to the base of operation or emergency shelter.
2. The system includes an **integrated solution for storing energy** at the base of operation or emergency shelter to ensure reliable power availability for required use.
3. The system includes a **smart integrated energy management** and distribution solution capable of coordinating energy generation, storage, and output in real-time, ensuring optimised operation according to varying energy demands, being remotely controlled and enabling monitoring.
4. One system provides **sufficient electrical power output** for an entire Base of Operation or Emergency Shelter for at least 15 persons at all times during the ongoing operation with different demands.
5. The system includes **energy conversion components** e.g. chemical to electrical energy with a low-emission and efficient approach.
6. The system is designed for **rapid deployment and transport in emergency** response operations, where space, weight, and handling capacity are limited. Therefore, it must be compatible with commonly used logistics and transport methods of emergency response organizations (modularity).
7. The system remains fully operational and robust under a wide range of **environmental conditions**, including extreme weather events such as high winds, heavy rain, dust, hail, and temperature extremes.
8. The system is designed for **low-maintenance operation** in field conditions, enabling sustained use during emergency deployments with minimal technical intervention. It allows for easy access to serviceable components, support quick replacement of parts using standard tools, and enable maintenance tasks to be performed by non-specialised personnel on site without the need for specialised infrastructure.
9. The system is designed for **rapid, intuitive installation and operation** in the field by non-specialised personnel. It supports plug-and-play functionality, requiring minimal setup steps, no complex configuration, and enabling safe and immediate use of energy outputs. The design facilitates deployment under time pressure and in challenging conditions, with clear visual indicators, standardised connections, and an interface that supports error-free operation.
10. The system is designed to enable **safe setup, operation, and basic maintenance** by non-specialised personnel, while allowing trained personnel to perform more advanced tasks with minimal training. Training requirements shall be limited in duration

11. The system is designed to support **modular scalability**, allowing multiple units to be interconnected in order to increase total power output and energy capacity. The system maintains operational stability and coordinates energy management when scaled to meet the demands of larger micro-grids.
12. The system is designed to **minimise noise emissions** during all modes of operation to ensure compatibility with sensitive environments such as resting and sleeping areas. Noise levels remain low enough to avoid disturbing personnel and affected populations.
13. As a preferred feature, the system is designed in accordance with **circular economy principles and sustainability goals**. This includes the use of recyclable or reusable materials, modular components for easy disassembly and repair, and consideration of low environmental impact across the entire lifecycle—from production and deployment to end-of-life disposal. Solutions that minimise resource consumption and promote long-term environmental performance are highly valued.
14. The system is designed and operates to ensure the **safety of personnel, equipment**, and the surrounding environment during all phases of deployment, transport, installation, operation, and maintenance. It prevents hazards such as electric shock, fire, explosion, mechanical injury, and environmental contamination under both normal and foreseeable fault conditions.

The supplier questionnaire was structured around these 14 categories, with only two specific requirements combined under the overarching category Safety:

- *"The system is designed to enable safe setup, operation, and basic maintenance by non-specialised personnel, while allowing trained personnel to perform more advanced tasks with minimal training. Training requirements shall be limited in duration."*
- *"The system is designed and operates to ensure the safety of personnel, equipment, and the surrounding environment during all phases of deployment, transport, installation, operation, and maintenance. It prevents hazards such as electric shock, fire, explosion, mechanical injury, and environmental contamination under both normal and foreseeable fault conditions."*

From these adjustments, the supplier survey was ultimately structured around the following 13 categories:

1. Renewable Energy Source
2. Integrated Generation, Conversion & Storage
3. Power Output
4. Smart Energy Management
5. Use of Commercial Fuels
6. Rapid Transport & Deployment
7. Intuitive Setup & Operation
8. Operation in Harsh Environments
9. Low-Maintenance Operation
10. Safety
11. Modularity & Scalability
12. Noise Emissions
13. Environmental Sustainability

The requirements were subsequently converted into yes/no questions, ensuring that suppliers encountered clear and easily understandable items in the survey, which they could answer with yes or no for their product or products.

The complete list of these questions is as follows:

- Q1: Does your system generate electrical energy from renewable energy sources?
- Q2: Does your product combine energy generation, conversion, and storage?
- Q3: Does your system include a smart energy management system?
- Q4: Is one unit of your system sufficient to power a standard emergency base of operations (approx. 10–15 kW continuous load)?
- Q5: Does your energy conversion system support at least one commercially available fuel (e.g., bio-based fuels, hydrogen, methanol, or sustainable synthetic fuels)?
- Q6: Is your system designed for easy transport?
- Q7: Easy transport specifics: Product fits on an EU pallet
- Q8: Easy transport specifics: Product is carriable by max. four persons
- Q9: Is your system designed for rapid deployment?
- Q10: Rapid deployment specifics: Product is suitable for air cargo deployment
- Q11: Rapid deployment specifics: Product is suitable for deployment on commercial aircraft
- Q12: Can your system maintain full functionality under harsh environmental conditions (e.g., heat, humidity, dust)?
- Q13: Is your system designed for low-maintenance operation and easy servicing in the field?
- Q14: Is your system designed for rapid, intuitive setup and operation by non-specialised personnel in emergency conditions?
- Q15: Does your system ensure the safety of personnel, equipment, and the environment throughout all phases of use (deployment, transport, installation, operation, maintenance)?
- Q16: Can your system be expanded or scaled up by adding modular components?
- Q17: Is your system designed to operate with minimal noise emissions? (e. g., dB(A))
- Q18: Is your system designed in accordance with circular economy principles and environmental sustainability? (e. g., recyclable, repairable, emission free/reduced)

To systematically reflect the responses, a traffic-light evaluation scheme was applied. Each answer was translated into a color-coded rating according to predefined thresholds:

- Red (non-compliant): requirement not covered (e.g. “No”, insufficient capacity, excessive noise, or “Not applicable”).
- Yellow (partially compliant): requirement partly covered, unclear, or insufficiently specified.
- Green (compliant): requirement reported as covered (self-declared), indicating alignment with the thresholds defined in Deliverable 2.3.

The results of the survey therefore provide initial insights into solution providers and their technologies. On the basis of this condensed requirement set, promising solutions could be identified for more detailed analysis in a potential next round. These will be subject to weighted requirement assessment and further technical and operational validation.

3. Technology fact sheets

3.1. Commercial of the Shelf technologies

3.1.1. Crystalline Silicon Photovoltaic Cells

Status:	Market available
Key words:	Photovoltaic (PV); Solar-energy; C-Si PV

Summary

Crystalline Silicon Photovoltaic Cells provide a reliable and efficient renewable energy solution for various applications. Their high efficiency and durability make them appear suitable for both permanent and mobile power generation. Key advantages include high efficiency, scalability, and relatively low maintenance. However, C-Si PV systems require significant space, have high initial costs, and depend on sunlight, necessitating and inverter and energy storage solutions for continuous power supply.

I. Technical Function and Description

Crystalline Silicon (C-Si) Photovoltaic (PV) Cells convert sunlight radiation directly into electricity using the photovoltaic effect. When light hits the silicon, it excites electrons, forming electron-hole pairs [18–21]. These are separated by an internal electric field at the junction of p-type and n-type silicon, generating voltage and current when connected to an external circuit [21] . At present, crystalline silicon PV cells the is most dominant PV -technology. Their high efficiency, reliability, and long-term stability have established them as the most widely adopted solar technology, suitable for both residential and large-scale commercial application, including in sunny remote areas.
The performance of C-Si PV technology is affected by several factors, including the intrinsic material properties of the semiconductor, environmental conditions (e.g., irradiance, angle of incidence, and temperature), and advancements in cell design (see Table 2). Two primary variants of c-Si wafers are used: monocrystalline and polycrystalline, each produced via a distinct method. Although polycrystalline production is simpler and cheaper, monocrystalline technology has become dominant because polycrystalline wafers typically have lower efficiency and higher fragility, giving monocrystalline wafers an overall performance advantage [22,23]. This technology similar to other electricity generating technologies requires a converter (such as inverters, DC/DC, AC/DC units) is needed. Thin and foldable C-Si PV designs are possible, but their flexibility is limited. Both foldable and semi-flexible C-Si PV designs also carry a higher risk of damage compared to rigid, thicker, conventional PV panels.

Table 2: Performance Metrics for C-Si-PV

Metric/Property	Value per Module
Power Output (W)	Maximum Power (Pmax) – The peak power output of the module under Standard Test Conditions (STC)- Individual c-Si solar cell 5 W to 10 W. A full 60-cell or 72-cell module/panel 235 – 700 W under STC per module (typically 300-400 under STC) [18,22,24] , 130-210 W/m² under commercial conditions [23]
Transport/Logistics	EU pallet compatible: Fits if stacked vertically; weight under 1500 kg; Carryable by 4 people: All subcomponents can be modularised below 120 kg ➔ 72 cells configuration panel (20–25 kg [25] ca.11 kg per m² ➔ 11.6 kg/m² Cargo aircraft transport: Fully feasible Commercial passenger aircraft: Only feasible for compact or specialised kits
Operational Robustness/ Durability	indicatively aligned with environmental robustness requirements subject to validation, especially regarding inverter altitude/heat performance
Maintenance	appear to be compatible with low-maintenance emergency deployment standards. They require only basic upkeep, support 24/7 autonomous use, and are modular for efficient in-field repair and support. Operational validation is required.
Rapid, Intuitive, and Safe Field Deployment	as modular emergency kits, C-Si-PV appears suitable for the criteria for safe, rapid, and intuitive deployment by lightly trained field teams, even under time pressure or harsh conditions
Training	likely suitable for rapid, scalable deployment with minimal training burden, offering intuitive operation for non-specialists and short onboarding for trained personnel
Modularity and Microgrid use	paired with compatible hybrid or off-grid inverters C-PV cell appear highly suitable for scalable micro-grid setups
Acoustic Performance	low-noise inverters and proper thermal design, suggests compliance with all specified acoustic limits, making them ideal for sensitive environments such as sleeping quarters
Circular Economy Principles	The C-Si-PV technology is partially aligned with circular economy principles, offering high recyclability, modular design, and long-term environmental performance (e- g- glass /aluminium). Some challenges remain with polymer recycling.
Safety	Safety labeling and operational guidance are consistent with relevant EU and IEC norms

*STC are standard laboratory conditions

II. Current Technological Development Trends/Development Trends & Market Analysis

Recent advancements in C-Si PV technology have focused on enhancing efficiency through innovations such as Passivated Emitter and Rear Contact (PERC) cells, bifacial modules, tandem cells, and heterojunction cells [18,26]. PERC improves performance by reducing recombination losses with a passivation layer on the rear surface. Bifacial modules increase energy yield by capturing light on both sides of the panel, while tandem cells, combining silicon-perovskite) surpass traditional limits by utilising a broader light spectrum [18,26]. Heterojunction cells combine amorphous and crystalline silicon to reduce surface recombination, achieving higher efficiencies [18,26].

The C-Si PV market continues to show dominance on the global solar industry, with silicon wafer-based PV technology accounting for approximately 97% of total production in 2023 [18] (for product examples and providers see Table 3 & 4). particularly China, which dominates over 95% of wafer and ingot production, 86% of module manufacturing, while Europe and North America contribute only to the total production 2% each [18]. However, the high concentration of manufacturing reliance of key-components (including inverters) in one region also presents potential supply risks. Hence, Europe and the USA, though a large market for PV energy, relies heavily on imports but is actively investing in local production and diversification and through political initiatives.

In general, we can see a market shift from subsidy driven to competitive pricing model. Owing to this price development, the International Energy Agency already proclaimed already in 2020 that it is now the *"cheapest source of new electricity generation in most parts of the world"* and the *"cheapest source of electricity in history" [27]*. This is particularly relevant for remote areas like rural regions with no connections to the grid and sufficient sunlight. Considering current market, deployment, and research trends, the technology is expected to become even cheaper, and when combined with other PV technologies and energy storage systems (addressing intermittency issues), it will be more efficient and competitive. Owing to this fact, in the near term, no other single renewable technology currently combines cost and maturity as effectively as C-Si PVs and their technical improvements e.g. with perovskite tandem cells. Other options, such as wind, hydro, or marine power, remain relevant as complementary solutions. Despite higher upfront costs, C-Si PV systems with lithium-ion storage are expected to reach cost parity with a 15-kVA diesel generator in roughly two years of continuous operation.
The analysis of patent data for crystalline silicon photovoltaic cells indicates that the field is predominantly driven by patent activity in China. An exception is the *Commissariat à l'énergie atomique et aux énergies alternatives* in France, which stands out with 34 active patent families, significantly more than any other organisation. From Germany, only the *Helmholtz-Zentrum Berlin*, *Green Roofs Planitka*, and *BASF SE* hold a single patent family each.
The number of scientific publications in this area rose around 2010 but has shown a slight and steady decline since then, suggesting that the topic is no longer at the forefront of scientific debate. Both the number of patents and publications are approximately 700, classifying crystalline silicon photovoltaics as a relatively small research field (see Annex 1).

Table 3: Global market key providers for Crystalline Silicon Photovoltaic Cells [28]

Company	Headquarters (Country)
SunPower Corporation	USA
JinkoSolar Holding Co., Ltd.	China
JA Solar Holdings Co., Ltd	China
Canadian Solar Inc.	Canada
Trina Solar Ltd.	China

Table 4: Examples for related products

Product	Seller	Link
EcoFlow 160 W portable solar panel	Ecoflow	Link
BLUETTI PV350 Foldable solar panel	BLUETTI	Link
SOLARWATT Panel vision M 5.0	Solarwatt	Link
Eco Line N-Type HJT GG BiF M13 up to720Wp	Luxor	Link
Vertex S+ 450 - 510 W+	Trinasolar	Link
Dragon Wings	Southern Beams	Link
Solbianflex panels-Custom-made C-Si panel	SOLBIAN	Link

III. Implications and Considerations for Emergency Response Organizations

C-Si photovoltaic systems provide emergency response organizations with a highly efficient, scalable, and fuel-independent source of no-emissions, quiet, and low-maintenance energy, especially suitable for rapid deployment in disaster zones with constrained fuel logistics or compromised infrastructure, without the noise or fuel dependency of traditional diesel generators.

From a logistical and deployment standpoint, C-Si PV systems must be securely transported by air or land, often under time pressure. While more fragile than diesel generators, they can be packed modularly for transport via cargo planes or helicopters [29]. Commercial passenger aircraft are only feasible for transporting compact or specialised kits. Field deployment can typically be completed within hours, in remote or off-road areas (depending on the numbers of panels and mounting system), with systems typically mounted on structures transported to these locations or constructed from local materials, then placed on stable surfaces and oriented for optimal sunlight.

Operationally, the systems require minimal upkeep, mostly routine cleaning and inspections, and can be monitored remotely or managed by personnel trained in a few hours [30]. Integration with battery storage or backup generators ensures continuous energy availability during night-time or cloudy periods, addressing the intermittent nature of PV- technology. Site-specific considerations such as dust, snow, and shading must be managed, and load prioritization protocols should be in place to safeguard power delivery to critical services.

Safety and security measures are vital. Installation risks, including electrical hazards, are mitigated through proper training and standardised procedures. Panels should be anchored securely to resist extreme weather and located in areas that reduce the risk of theft or vandalism [31]. Weather-resistant materials and tamper-resistant mounting systems, commonly used for conventional rigid panels, enhance reliability and physical security, while ongoing monitoring ensures operational safety in diverse environments [ibid.].

In terms of societal acceptance and ethics, C-Si PV systems are generally well received due to their quiet operation and visible sustainability benefits, especially compared to wind turbines. However, concerns persist regarding land use, since they require more space than diesel generators, along with waste handling and supply chain ethics [32].

3.1.2. Thin-Film Photovoltaic

Status:	Market available
Key words:	Solar, Second-generation (2G), thin, flexible, PV, light-weight

Summary

Thin-film photovoltaic (TFPV) technology offers significant advantages for emergency response operations due to its lightweight, flexible, and portable design. Unlike traditional crystalline silicon panels, TFPV can be integrated into various surfaces, deployed quickly, and transported easily, making it appear promising for off-grid and rapid-response scenarios. Its key benefits include lower weight, adaptability to diverse environments, and good performance in low-light and high-temperature conditions. However, they generally have lower efficiency compared to conventional solar panels and may require more surface area to generate the same power output. Also, as other PV-technology, they depend on sunlight, necessitating energy storage solutions for continuous power supply. Despite these limitations, its ease of installation, low maintenance, and ability to provide clean, decentralised energy make a relevant solution for POWERBASE.

I. Technical Function and Description

Thin-film photovoltaic (TFPV) devices represent the "second generation" of PV cells. Instead of sawing 200 µm-thick crystalline-silicon wafers, TFPV is produced by depositing ultra-thin semiconductor layers, only a few nanometres to tens of micrometres thick, onto rigid or flexible substrates such as glass, metal foil, or plastic [33–35]. This layer-by-layer approach, achieved through techniques like sputtering, evaporation, or solution processing, allows precise tailoring of each functional layer for maximum performance. Although they can also be deployed as rigid more conventional PV panels (such as crystalline-silicon PV), we focus on the main advantage of TFPV technology: Its rollable formats (see Table 5).
All TFPV stack contains five key layers that can in different orders [36]. The substrate supplies mechanical support. A transparent conducting oxide (TCO) follows, doubling as the front electrode while admitting light [37–40]. Next, a very thin window (buffer) layer forms a low-resistance heterojunction with the absorber layer—the core region where incoming photons create electron-hole pairs. An internal electric field in the absorber separates these charges, pushing electrons toward the TCO and holes to the rear, thereby generating voltage [41]. A reflective metal back contact collects the holes and recycles unabsorbed light [36,41].
Because the active material is coated directly onto the substrate, TFPV modules are lightweight, bendable, and can be monolithically interconnected during fabrication, simplifying wiring compared with crystalline-silicon panels [37–40]. The drastic thickness reduction cuts material use and permits roll-to-roll production, enabling rapid scale-up.
The resulting benefits; mobile, low weight, flexibility, mechanical resilience and comparable robustness (in comparison to thin crystalline-silicon PV), make TFPV a suitable solution for building-integrated photovoltaics, portable electronics, vehicles, and tent tarpaulin. However, they can also be rolled out easily to cover large areas, highlighting their rapid-installation capability off-grid.
There are three different subtypes of TFPV: 1) Amorphous-silicon (a-Si) thin films are ultra-light, highly flexible and tolerate diffuse light, yet their module efficiency is the lowest (≈9–13 %) and falls further due to light-induced degradation, so large surface areas are needed [36]. 2) Copper–indium–gallium–selenide (CIGS) devices achieve the highest laboratory efficiency of any thin film (~21 % on single cells) and maintain strong

output in heat and shade while remaining compatible with bendable substrates; the trade-offs are reliance on scarce indium/gallium, toxic selenium compounds in production and a relatively complex, costlier process [Ibid]. 3) Cadmium-telluride (CdTe) technology is manufactured by a simple, low-temperature sequence that delivers the lowest cost per watt and the current commercial module efficiency record (≈16-20 %) [Ibid]. Its downsides are cadmium toxicity, concerns over limited tellurium supply and the fact that most CdTe modules are built on rigid glass, restricting flexibility undermining the key benefit of TFPV-technology.

If transport is difficult and speed of deployment is critical, flexible copper-indium-gallium-selenide (CIGS) on metal or polymer foil is usually the best choice. It arrives in lightweight, rollable reels that fit into small cargo spaces, can be unrolled and adhered directly to roofs, tents or curved structures in minutes, and, unlike amorphous-silicon, its higher efficiency keeps the required surface area. Hence, CIGS appear to be the most promising subtype in the context of Powerbase, subject to confirmation of performance and logistics in field trials.

The analysis of patent data in the field is predominantly driven by patent activity from Asia (notably China, Japan, and Taiwan). Among the top 20 patent applicants are also two U.S.-based companies, First Solar Inc. and Applied Materials Inc., as well as Saint-Gobain from France. Further down the ranking are German companies such as Schott AG and CTF Solar GmbH.

With nearly 3,500 patents, the topic appears to be relatively well-researched. This is also reflected in the scientific literature: following a surge in publications between 2010 and 2015, academic interest has declined markedly over the past decade (see Annex 1).

Table 5: Performance Metrics for Thin-Film PV

Metric/Property	Value per Module
Power Output (W)	91 W (A-sil)-216 W CIGS per m² under Standard testing conditions (STC) (under operational sunny conditions 80% of STC output) [36]
Transport/Logistics	Highly favourable for logistics: lightweight rolls (low -weight small space) that ship cheaply with minimal breakage risk, while glass
Operational Robustness/ Durability	Appear as relatively robust in harsh environments and survives drops and scratches and flexing far better than glass-framed crystalline panels
Maintenance	Reported to be low for A-sil. Clear debris off the panels is needed to help them stay efficient. Have the entire system serviced regularly to keep it running at optimal efficiency [42,43]
Rapid, Intuitive, and Safe Field Deployment	Flexible TFPV sheets can typically be rolled out and connected intuitively within minutes
Training	Mostly reported as “plug-and-play” compatible, thanks to their uniform 30–50 V blocks and widespread inverter support,
Modularity and Microgrid use	Pairable with other technologies or scaled up with “plug-and-play” thanks to their uniform 30–50 V blocks and widespread inverter support
Acoustic Performance	Low, can whistle under strong winds flexible sheets may flap in up to 50–60 dB(A)
Circular Economy Principles	Low: Thin-film PV has a quick energy payback and modest material use, but its circular-economy performance is limited by shorter lifetimes, scarce-metal dilution, and still-immature recycling infrastructure

Safety	TFPVs are lighter and avoids glass cuts, yet still carries high-voltage shock risk and can release trace heavy-metal dust when damaged, so gloves and proper e-waste disposal remain essential

II. Current Technological Development Trends/Development Trends & Market Analysis

Current trends in TFPV R&D focus on increasing efficiency, reducing material use, and enabling flexible, lightweight applications (for product examples and providers see Table 6 & 7). Advances include roll-to-roll manufacturing, optimised bandgap grading, and integration with perovskites for tandem cells exceeding 21% efficiency. Their durability and flexibility make it ideal for building integration [44], portable electronics and vehicles with curved spaces [45].
CdTe and CIGS dominate the thin-film PV market due to their low production costs and high efficiency. Their continued growth is supported by scalable manufacturing and diverse applications, though reliance on rare materials like cadmium, tellurium, indium, and gallium poses supply risks [45]. China, the U.S., and Japan are key players in the supply chain, with First Solar leading in CdTe and a more fragmented market for CIGS, including several European manufacturers [45]. However, comparing it to regular C-Si PV, the thin-film market remains relatively small, with competitiveness limited to niche applications.

Table 6: Global market key providers for Thin-Film Photovoltaics [46]

Company	Headquarters	Thin-Film PV Focus
First Solar, Inc.	Arizona, USA	CdTe
Kaneka Corporation	Japan	a- silicon
Solar Frontier K.K.	Japan	CIGS
NanoPV Solar Inc.	New Jersey, USA.	a- silicon
SoloPower Systems, Inc	Oregon, USA	CIGS

Table 7: Examples for related products

Product	Seller	Link
FS-387 3 black (CdS/CdTe)	PVExchange/First Solar	Link
Renogy 150W CIGS Solar Panel	RENOGY	Link
BougeRV Yuma CIGS 100W	Bouge RV	Link
Moolsun 80W 18V CIGS Flexible Solar Panel Film ETFE Waterproof DIY	Moolsun	Link
Renowise CIGS	Solarbuy.com /RENOWISE	Link
Mobile solar tents, solar canopies & solar sails (no specific product names)	pvilion	Link
Mobile solar tents, solar canopies & solar sails (no specific product names)	Tarpon Solar	Link
Rollable Solar Panels	PowerFilm Solar	Link

III. Implications and Considerations for Emergency Response Organizations

TFPV systems may offer significant logistical advantages for emergency response operations due to their lightweight and flexible form factors. Their ability to fold and be compactly packaged reduces volume and eases handling, allowing efficient transport even in areas with poor infrastructure. Modules can be delivered via drones, all-terrain vehicles, or helicopters, and smaller units can be carried by individual responders. To prevent damage during air transport from pressure changes, humidity, or temperature extremes, robust protective casing and shock-absorbent packaging are essential.

TFPV systems are designed for rapid deployment, allowing integration directly onto tents[12], shelters, or vehicles without complex mounting structures. Their flexibility enables secure attachment using adhesives, Velcro, or integrated fasteners, which simplifies setup and accelerates energy access in critical zones. In remote or infrastructure-poor environments, adhesive-backed panels or portable mounting frames can be used to establish power sources quickly. Minimal tools and moderate training make TFPV installation efficient and scalable, which is essential during time-sensitive disaster response.

Once installed, TFPV panels require limited maintenance, mainly involving periodic cleaning to remove dust or moisture and preserve energy yield. Their low degradation rates and ability to endure typical outdoor conditions contribute to reliable operation. However, flexible panels can be more prone to physical damage compared to thick rigid alternatives with additional protective layers, particularly under extreme environmental stress. Basic training in handling and maintenance practices ensures longevity and optimal performance, with modular designs allowing seamless integration into broader power systems with storage components.

Deploying TFPV in emergency zones demands attention to safety risks like electrical hazards during installation, which can be mitigated through training and use of Personal protective equipment like gloves. Security is another concern, as lightweight, portable panels are susceptible to theft in remote locations. Surveillance systems, secure fencing, and GPS tagging are effective deterrents. Additionally, weather events such as hail or storms pose a risk to exposed panels; therefore, temporary deinstallation and storage during severe weather could be planned for system protection for long-term robustness.

While direct studies on social acceptance of TFPV are limited, it is likely to mirror the generally favourable perception of conventional solar technologies. Positive acceptance is likely, due to its clean energy profile and non-intrusive deployment, especially when compared to wind installations. However, concerns over the use of toxic materials like cadmium and lead raise ethical considerations regarding environmental impact and end-of-life disposal.

[12] Depending on requirements by trent provider / there might be restrictions on additional load etc.

3.1.3. Small Hydro Generators

Status:	Market Available / Research & Development
Key words:	Small Hydro, Run-of-River, Head, Decentralised Hydropower, Micro Hydro Systems,

Summary

Small Hydro Generators (SHGs) are compact hydropower units that generate electricity from low to medium head water flows. Their performance depends on water flow (Q) and vertical head (H), and common turbine types include Kaplan and Pelton. SHGs can be deployed rapidly, where suitable hydrological conditions exist. They operate without fuel and can be integrated into hybrid systems. Their low environmental impact, high efficiency, and suitability for decentralised off-grid energy systems, could mark SHGs as valuable for resilient power supply, especially in remote and/or mountainous regions.

I. Technical Function and Description

Small Hydro Generators are renewable energy systems that harness the kinetic and potential energy of flowing water to generate electricity. These systems fall under small-scale hydropower and are categorised based on capacity: systems under 10 kW are termed Pico-Hydro, serving individual households, remote cabins, or agricultural needs; systems from 10–100 kW are classified as Micro-Hydro, aimed at small communities, off-grid installations, or light industrial use; and Mini-Hydro systems, with capacities of 100 kW to 10 MW, are suited for larger communities, commercial operations, or feeding power into national grids [47,48]. Unlike large-scale hydropower, which often requires significant infrastructure such as dams and reservoirs, small-hydro systems can operate without large water storage, minimising environmental disruption [48,49].
Typical systems operate with heads between 2–50 meters and flows from 0.1 to 10 m^3/s (see Table 8). Depending on site conditions, Pelton, Francis, or Kaplan turbines are used [47,50]. Most small hydro systems include generator designs rated for 10–500 kVA, often air-cooled and optimised for flow variation using fixed-blade or Kaplan-type turbines [51]. Run-of-river designs eliminate the need for large reservoirs, reducing environmental impact. Systems can be grid-connected or operate in island mode, providing base load or backup power for villages, industrial sites, and emergency facilities. Efficiency ranges from 70–90% depending on design and maintenance [48,49]. Technological advances include modular turbine-generator sets, standardised containerised systems, and improved remote monitoring. Some setups integrate with solar or battery systems for hybrid microgrids [49,50]. Compact systems are often installed in remote or mountainous terrain, operating autonomously with minimal intervention potentially for decades (20–50 years) [52,53].

Table 8: Performance Metrics for Small Hydro Generators

Metric/Property	Value per Module
Power Output (W)	Varies by scale: pico (<5 kW), micro (5–100 kW), mini (100 kW–1 MW), small (1–10 MW) [47,53,54]
Transport/Logistics	Modular containerised units available; scalable deployment in remote/off-grid areas [55,56]
Operational Robustness/ Durability	Systems can be containerised or trailer-mounted for field deployment [50,56]
Maintenance	Operable off-grid; often used in hybrid or microgrid settings [52,54]
Rapid, Intuitive and Safe Field Deployment	Run-of-river systems can be intermittent; storage solutions enhance stability. Deployment speed is strongly dependent on the local hydrologic conditions (flow rate Q and head H). The appropriate turbine technology must be preselected according to these site parameters; true “rapid” field installation is therefore limited to well-suited locations. [47,50]
Training	Typically low compared to larger hydro, though operational demands (sediment management, maintenance) require specific technical training [48,54]
Modularity and Microgrid use	Long lifespans (>25 years); tested in harsh rural settings [52,56]
Acoustic Performance	Sensitive to water variability, but newer systems integrate buffering or storage [48,50]
Circular Economy Principles	Depending on design, maintenance, and material quality; evidence limited on recyclability or modular reuse [53,54]
Safety	Low noise; suitable for sensitive environments [55,56]

II. Current Technological Development Trends/Development Trends & Market Analysis

SHGs are evolving in the last decade through innovations in compact turbine design, modular deployment, and smart grid compatibility (for product examples and providers see Table 9 & 10). Efforts focus on reducing civil infrastructure needs via prefabricated intakes and penstocks and enhancing adaptability through containerised or skid-mounted units. Constraints include permitting, sedimentation, and seasonal flow variability. However, hydro potentials in canals and water supply lines are increasingly explored [53].

The development of Internet of Things (IoT)-enabled hydro systems provides real-time performance monitoring through cloud-based analytics. These innovations allow remote troubleshooting, reducing downtime and improving operational efficiency in disaster-prone and remote locations [56]. Additionally, Artificial Intelligence (AI) and machine learning models are being utilised to optimise water flow management, enhancing efficiency while minimising energy loss. These AI-driven systems automatically adjust turbine settings based on real-time flow conditions [53].

Increased Government investment, policy support and climate funding (e.g. GCF, EU Green Deal) drive SHG expansion as a sustainable alternative to diesel generation in rural electrification [48].

Global players include Voith, Andritz Hydro, and GE Renewable Energy. In the micro-hydro segment, smaller companies like Turbulent (Belgium), PowerSpout (New Zealand), and Smart Hydro Power (Germany) offer plug-and-play systems. Market growth is projected at 2.5–3% annually until 2030, with increasing relevance in decentralised grids [57–59].

The topic SHGs has over 10,000 active patent families and can thus be classified as a large research topic. The leading patent applicants come from Russia and China, while Germany is represented far behind by *Voith Patent GmbH*. In comparison to the patents, there are relatively few publications, which have also been decreasing annually since around 2017 (see Annex 1).

Table 9: Global market key providers for Small Hydro Generators [57–59]

Company	Headquarters (Country)
Voith Hydro	Germany
Andritz Hydro	Austria
GE Renewable Energy	USA
Bharat Heavy Electricals Ltd.	India
Siemens Energy	Germany
Canyon Hydro	USA

Table 10: Examples for related products

Product	Seller	Link
Turbulent Micro Hydro	Turbulent	Link
Smart Hydro Power Turbine	Smart Hydro Power	Link
PowerSpout LH	PowerSpout	Link
Waterotor WET-x	Waterotor	Link
Idénergie River Turbine	Idénergie	Link
Different Types	Suneco Hydro	Link

III. Implications and Considerations for Emergency Response Organizations

SHGs can provide reliable electricity where hydrological conditions are favourable (e. g. in in water-rich remote areas). Many modern systems can be airlifted, transported via light trucks, or assembled on-site within days, streamlining logistics and enabling rapid field deployment [48]. This makes them viable for emergency response operations, especially in mountainous disaster zones [53]. Once installed, SHGs provide autonomous, low-maintenance baseload power independent of fuel logistics, though seasonal flow variation and sedimentation may affect year-round reliability [50]. To enhance operational resilience, systems now feature corrosion-resistant materials, self-cleaning intakes, and automated emergency shutoffs [50]. Their low noise emissions and environmental impact may be suitable for ecologically sensitive or densely populated settings. Paired with batteries, they ensure 24/7 availability and cover peak demands. Environmental considerations are addressed through run-of-the-river setups that avoid large-scale habitat disruption and through community involvement in site planning to ensure local support [47,53]. Their long service life (>25 years) makes them sustainable for long-term reconstruction and rural development. However, feasibility depends on hydrology, topography, and regulatory factors. Emergency planners must pre-identify suitable sites or integrate SHGs in early-stage reconstruction planning.

3.1.4. Small Wind Turbines

Status:	Market available / in Research and Development
Key words:	Small wind turbines, renewable energy, decentralised systems, wind turbines, microgrid integration

Summary

Small Wind Turbines (SWTs) are decentralised renewable energy systems typically rated below 100 kW, used to provide electricity in remote, hybrid, or grid-connected settings. By exploiting wind energy, they contribute to carbon footprint reduction, energy independence, and resilience in energy supply. Due to their relatively low cost, mechanical simplicity, and scalability, SWTs can be suited under favourable wind conditions for use in microgrids, off-grid homes, telecom towers, agricultural systems, and emergency deployments.

I. Technical Function and Description

Small Wind Turbines (SWTs) are defined as wind energy systems with a capacity of up to 100 kW, designed for localised energy production (see Table 11). Different sub-types of SWTs include horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs) [60]. HAWTs are the more traditional design, featuring a horizontal rotor axis and typically higher efficiency in steady wind conditions. They achieve higher efficiency in rural or open areas with consistent wind flows. VAWTs, on the other hand, vertical rotor axis, suit in urban environments with turbulent or multi-directional wind flows. VAWTs may often be more compact and quieter (acoustic levels range from 40–65 dB(A)), which fit them for residential and urban applications, suitable for sensitive or residential zones [60–64].
Small wind turbines operate by converting wind energy into electrical energy through different interacting components. Rotor blades capture wind energy by rotating parallel and drive the generator. This generator converts this mechanical energy into electrical energy. Direct-drive generators are increasingly preferred for their reduced maintenance and higher efficiency [60]. To optimise wind capture, a tower is used, especially in need for HAWTs. Height is critical as wind speed and consistency generally increase with altitude. Advanced tower designs, such as self-rising lattice structures, are being explored to improve transportability and reduce installation time [63,65]. Inverter and control systems regulate power output and are typically designed to allow compatibility with other energy systems. Maximum Power Point Tracking (MPPT) systems are often used to optimise energy output under variable wind conditions [62].

Table 11: Performance Metrics for Small Wind Turbines

Metric/Property	Value per Module
Power Output (W)	Typical: 300 W – 100 kW; Common: 1–10 kW [61]
Transport/Logistics	Lightweight (20–500 kg); modular kits; mobile trailer setups exist [62]
Operational Robustness/ Durability	Reported design life: 15–25 years; robust in winds up to 50 m/s [66]
Maintenance	Low; annual visual inspections, bolt tightening, lubrication [60]
Rapid, Intuitive, and Safe Field Deployment	Can be installed within a day under favourable conditions; installation time may vary depending on terrain and resources; no concrete needed for some mobile systems [62]
Training	Basic electrical/mechanical skills; intuitive setup with manuals [66]
Modularity and Microgrid use	High; compatible with hybrid PV/diesel systems [67]
Acoustic Performance	40–65 dB(A) depending on turbine type and wind speed [63,64]

Circular Economy Principles	Recyclable materials (aluminium, composite blades); long lifetime [60]
Safety	Built-in overspeed brakes, lightning protection, and tilt-up masts [66]

II. Current Technological Development Trends/Development Trends & Market Analysis

Trends and developments are in design and components. The electromagnetic design, including the use of rare-earth magnets, have enhanced energy conversion efficiency at low rotational speeds. Additionally, portable generators designed for deployable SWTs can integrate seamlessly into microgrid systems, enabling hybrid energy generation in remote or emergency applications. Field tests demonstrate that asynchronous generators in these systems can support more stable output under variable wind conditions, enhancing reliability during mission-critical operations [61,64,67]. Manufacturers increasingly offer systems bundled with solar PV and battery storage for microgrids. Some SWTs now include GSM/Wi-Fi telemetry for diagnostics.

Trends include blade pitch control, auto-furling, and modular plug-and-play architectures [60,62,66]. The aerodynamic performance of blades can be optimised using advanced air foils which are distributed scientifically along the blade radius to improve performance. These air foils maximise lift-to-drag ratios (LDRs) and enhance energy capture even in low Reynolds number environments [62,63,66]. Additionally, material selection for blade durability is critical, as exposure to environmental stresses can lead to surface corrosion. Protective coatings, such as anti-corrosion epoxy layers, are being integrated to ensure longevity under harsh conditions [65]. Novel blade manufacturing techniques, including additive manufacturing and fibre composites, aim to further improve structural reliability and reduce production costs [64,67].

A small number of firms (Ryse Energy, Uprise Energy, Bornay, Windside) dominate the market (for product examples and providers see Table 12 & 13). Emerging applications include offshore platforms, EV charging, and telecom relay power. Global growth is projected at 6–8% annually due to demand for clean, resilient distributed energy systems [63,65].

Only a limited number of patents related to SWTs have been identified, the majority of which originate from Asia. The low volume of scientific publications may indicate that the technology is either not well represented within the academic research landscape or comprises several distinct technological components that are investigated separately, thereby complicating the identification of relevant literature (see Annex 1).

Table 12: Global market key providers for Small Wind Turbines [68,69]

Company	Headquarters (Country)
Ryse Energy	UAE/UK
Bergey Windpower Co.	USA
SD Wind Energy	UK
Aeolos Wind Energy	Finland
Wind Energy Solutions	Netherlands
superwind	Germany

Table 13: Examples for related products

Product	Seller	Link
Aeroleaf™	New World Wind	Link
Uprise Energy Mobile Power Station	Uprise Energy	Link
SD Wind Energy SD6	SD Wind	Link
Bornay 6000	POWERACU	Link
E-3 – E-60	Ryse Energy	Link
Halo 6.0 Ducted Turbine	Halo Energy	Link

III. Implications and Considerations for Emergency Response Organizations

SWTs provide rapid and fuel-free energy solutions in disaster zones, field operations, and emergency shelters. Deployable systems with trailer or tilt-up towers are field-ready within hours, requiring minimal infrastructure [61]. Their low acoustic footprint and no-fuel operation make them suitable for sensitive settings [63,65]. Hybrid SWTs with solar and storage offer stable output and lower diesel dependency [62,63,66]. SWT systems support communications, refrigeration, water pumping, and medical operations during blackouts [61,67,70]. Recent trends point to increased use of SWTs in defence logistics and mobile humanitarian infrastructure, especially in conflict or disaster-prone regions [61,71]. Limitations include dependence on wind resource quality, required technician skills, and mechanical maintenance cycles. Nevertheless, in moderate wind zones, they offer reliable, sustainable alternatives to fossil backup generators [64].

3.1.5. Lithium-Ion Batteries

Status:	Market available
Key words:	Battery, Lithium-ion, LIB(s), NMC, LFP, NCA, LMO

Summary

Lithium-Ion batteries offer significant advantages for various energy storage applications due to their high energy density, efficiency, and rechargeable capability. Their lightweight and compact design makes them suitable for portable power solutions, supporting critical systems in off-grid scenarios. Key benefits include long cycle life, fast charging, and compatibility with other energy-technologies. However, challenges such as safety risks from thermal instability, high costs, and specific transportation regulations and the related risk of thermal runaways. Despite these limitations, lithium-ion batteries remain a relevant energy storage solution in the context of POWERBASE.

I. Technical Function and Description

Lithium-Ion batteries (v) are rechargeable electrochemical energy storage systems that operate by shuttling lithium ions between an anode and a cathode. Unlike disposable batteries based on irreversible reactions, LIBs allow for repeated charge and discharge cycles [72]. Their high energy density, lightweight design, and long lifespan make them widely deployed in both mobile electronics and stationary energy systems (see Table 14). Their transformative impact was recognised with the 2019 Nobel Prize in Chemistry [72].

A LIB pack consists of multiple cells, grouped into modules and assembled into battery packs. For high-power applications like electric vehicles (EVs), thousands of cells may be used [73,74]. Each cell includes an anode (usually graphite), a cathode (varies by chemistry), a liquid electrolyte, and a separator [75]. Standard cell voltage ranges from 2.5 to 4.2 V [76].

Key Cathode Chemistries:

- **NMC (Nickel Manganese Cobalt Oxide)**: Widely applied in EVs and grid storage for its balance of energy density (150-250 Wh/kg), power, and cycle life. Higher nickel boosts energy but reduces thermal stability [77–79]
- **NCA (Nickel Cobalt Aluminium Oxide):** Is reported to reach high energy densities (210–600 Wh/L) and is used in long-range EVs. However, is reported to have lower thermal stability and demands precise thermal management [80]
- **LFP (Lithium Iron Phosphate):** Has lower energy density (220–250 Wh/L) but are generally regarded as safer and thermally more stable, though with lower energy density, thermal stability, and long cycle life. Widely used in stationary storage and entry-level EVs [78,79]
- **LMO (Lithium Manganese Oxide):** Has been applied where fast ion diffusion is advantageous, though it has lower energy density (100–150 Wh/kg) and faster degradation. Often blended with NMC in hybrid cathodes [77]

Table 14: Performance Metrics for LIBs

Metrics/Property	Typical Values for a Pack
Power Output (W)	LMO (Lithium Manganese Oxide) can provide comparatively high-power output (up to ~5,000 W/kg) due to fast ion diffusion, though it suffers from faster degradation. LFP (Lithium Iron Phosphate) provides a balanced performance (~2,000–3,000 W/kg), combining good power capability with excellent thermal stability and safety. NMC/NCA chemistries are optimised for energy density and have moderate power output, making them suitable for long-range EVs rather than high-power applications [81,82]
Transport/Logistics	A portable lithium-ion battery system with a total mass of up to 150 kg can deliver power outputs in the range of approximately 300–500 kW, particularly when using high-power NMC or LFP cells with good thermal management. In contrast, container-based lithium-ion systems can deliver several MW of power, making them suitable for grid storage, renewable energy buffering, or fast-charging infrastructure [83,84]
Operational Robustness/ Durability	Lithium-ion batteries exhibit high operational robustness, particularly when advanced cathode materials (e.g., NMC, LFP) and optimised manufacturing processes are used. Durability is strongly influenced by cell chemistry, operating temperature, and structural integrity of components, with LFP batteries demonstrating particularly strong resistance to thermal and mechanical degradation [79,80]
Maintenance	Lithium-ion batteries are characterised by low routine maintenance needs due to integrated Battery Management Systems that handle most diagnostics and control functions. However, in high-demand or long-term storage systems, regular monitoring of temperature, voltage stability, and predictive software-based analysis remains essential for optimising performance and safety [78,79]
Rapid, intuitive, and safe field deployment	Modern lithium-ion battery systems, especially in containerised or modular formats, are designed for relatively rapid deployment through integrated battery management systems, pre-configured modules, and standardised thermal safety mechanisms. These features enable efficient, secure installation even in remote or mobile applications such as microgrids or temporary power supply [84,85]
Training	Training requirements for lithium-ion battery systems depend on application complexity. For modular or containerised systems, operator training typically ranges from one to three days and includes basic safety procedures and BMS operation. Systems designed for mobile or grid use often emphasise intuitive interfaces to reduce training demands [84,85]
Modularity and Microgrid use	Modular lithium-ion battery systems are suitable for microgrid applications due to their scalability, standardised interfaces, and ease of deployment [84]
Acoustic Performance	Lithium-ion battery systems are generally regarded as low-noise under normal operation, producing minimal audible noise. Any acoustic emissions primarily originate from cooling fans in large storage units or mechanical cell stress, which remain below thresholds of human annoyance [86,87]
Circular Economy Principles	Lithium-ion batteries are increasingly integrated into circular economy strategies through second-life applications and advanced recycling technologies [88]
Safety	Lithium-ion battery safety is primarily threatened by thermal runaway and fire risks due to overheating, overcharging, or mechanical abuse. To mitigate these hazards, modern systems employ robust thermal management, advanced separators, and intelligent battery management systems to detect faults early and maintain safe operation [89,90]

II. Current Technological Development Trends/Development Trends & Market Analysis

The market for LIBs has seen substantial growth over the past decade, driven primarily by increasing demand in various sectors, including consumer electronics, EVs, and renewable energy storage systems [91]. Consequently, commercial availability has increased, although regional access can vary depending on local manufacturing capabilities and supply chain logistics (for product examples and providers see Table 15 & 16). Pricing for LIBs has generally been on a downward trajectory, mainly due to technological advancements, economies of scale, and heightened competition among manufacturers [91]. However, fluctuations in the prices of raw materials, particularly lithium, cobalt, graphite, and nickel can significantly affect overall battery costs. The supply chain for LIBs is intricate, involving multiple stages such as raw material extraction, processing, battery manufacturing, and distribution. Key materials are primarily sourced from a few specific regions, which adds complexity to the supply chain. In response to growing demand, production of LIBs has increased significantly.

The field of LIBs is characterised by a high volume of both patents and scientific publications. In addition to the dominant Chinese patent applicants, Robert Bosch GmbH has filed over 300 patents, while BMW AG, the Volkswagen Group, and BASF SE have each contributed more than 100 patents.

Lithium-ion batteries are already deployed in a wide range of applications, which contributes to the diversity of the research landscape. The field remains the subject of active scientific investigation and continues to receive significant research attention and support (see Annex 1).

Table 15: Global market key providers for Li-ion-battery [92]

Company	Country of origin	Technology Focus
CATL	China	EV batteries & energy storage, leader in LFP batteries, who now also produces in Hungary
BYD Company	China	EV batteries & energy storage, pioneer of the Blade Battery (LFP technology), fully integrated EV supply chain.
LG Energy Solution (LG Chem)	South Korea	EV & energy storage batteries, focus on NCM (Nickel Cobalt Manganese) chemistry, strong global partnerships.
Panasonic Corporation	Japan	EV & consumer electronics batteries, specialises in NCA (Nickel Cobalt Aluminium) chemistry, Tesla's key supplier
Tesla Inc.	United States of America	EV & energy storage batteries, partners with Panasonic & CATL

Table 16: Examples for related products

Product	Seller	Link
EcoFlow DELTA Pro 3 Portable Powerstation (LFP & human-portable)	Ecoflow	Link
Anker SOLIX F3800 (LFP & human-portable)	Anker Solix	Link
BLUETTI AC300 (human-portable)	Solarwatt	Link
Battery Mobile X (Container LFP)	Alfen	Link
TPS HV 80 (Container, NMC)	TESVOLT	Link

III. Implications and Considerations for Emergency Response Organizations

Lithium-ion batteries (LIBs) may provide a promising storage option for emergency response organizations, especially when integrated into hybrid systems (e. g. with diesel generators or renewable energy sources). In such configurations, LIBs can reduce fuel consumption, emissions, noise, and maintenance needs compared with diesel-only operation, making them well-suited for temporary field deployments. Nevertheless, their use requires careful planning regarding logistics, safety, and operational reliability.

Transporting LIBs is subject to strict international regulations due to fire hazards. Cargo flights are permitted under conditions, while commercial flights impose limits (max. 160 Wh per battery) [85]. Proper packaging, labelling, and stable site selection with minimal environmental risk are crucial. Battery swapping could reduce local downtime and improve logistics near the grid [93]. This approach involves replacing depleted batteries with fully charged units but requires trained personnel and transport infrastructure. LIBs are also more modular and customizable than diesel generators, enabling scalable deployment.
Safety is a core concern, especially under extreme temperatures, vibrations, or poor maintenance. Risks such as thermal runaway, overcharging, and internal short circuits may cause fires or explosions. Mitigation measures include battery management systems (BMS), stable chemistries like LFP, and improved thermal protection designs [89]. Environmental stressors like dirt, humidity, and vibration can affect performance and lifespan. Therefore, shock protection, thermal management, and scheduled maintenance (including inspections for swelling or leakage) are critical. Personnel training and compatibility with camp infrastructure are also key for reliable operation [72]. Despite these advantages, geopolitical and ethical concerns persist. China

dominates the supply chain for LIB components, increasing dependency risks [94]. Resource extraction in countries like the DRC and South America raises issues of child labour, water use, and Indigenous land rights [95–97].
Recycling, lifecycle management, and avoiding planned obsolescence remain critical challenges for long-term sustainability [98].

3.1.6. Hydrogen Storage

Status:	Market available
Key words:	H2

Summary

Hydrogen Storage is frequently positioned as a key element in the development of a hydrogen economy. Among the various storage methods, compressed hydrogen (CGH_2) and liquid hydrogen (LH_2) are two of the most widely used options, each offering distinct advantages and challenges. Both approaches are commercially available but differ significantly in infrastructure needs, cost, and operational risks. Compressed hydrogen relies on high-pressure containment (typically 350–700 bar) to achieve sufficient energy density, *but at the cost of significant energy consumption for liquefaction and boil-off losses*. In contrast, liquid hydrogen storage involves cryogenic cooling to -253°C, enabling higher volumetric energy density but at the cost of significant energy consumption for liquefaction and boil-off losses. The benefits of hydrogen storage, such as high gravimetric energy density and long-term storage capability (while volumetric density remains significantly below liquid fuels), position it as a potential solution under appropriate conditions. The technology's potential impact on emergency operations is significant, though this requires specialised logistics and trained personnel.

I. Technical Function and Description

Stored hydrogen refers to hydrogen gas that has been captured and maintained for later use as an energy carrier. Key storage technologies include compressed gaseous hydrogen (cGH_2) in high-pressure tanks (200–950 bar), liquid hydrogen (LH_2) at -253°C, underground storage (e.g., salt caverns), and material-based methods like hydrides or LOHCs. Each method differs in cost, efficiency, and scalability [99] (see Table 17).
The main advantage of hydrogen storage lies in its high energy density and long-term stability; however, volumetric density remains low compared to liquid fuels and batteries. Liquid hydrogen offers superior gravimetric energy density, while compressed gas enables faster deployment. Underground storage is particularly cost-effective for large-scale applications [99]. In disaster relief, hydrogen can serve as a clean, zero-emission power source for medical units, communication, and water systems in off-grid areas.
Hydrogen storage is considered a core enabling function for the hydrogen economy, with compressed gaseous hydrogen (cGH_2) and liquid hydrogen (LH_2) being the most common options. cGH_2 uses high-pressure tanks (typically 350–700 bar), allowing moderate energy density and fast refuelling. LH_2 is cryogenically cooled to -253°C, offering higher volumetric energy density, though requiring significant energy for liquefaction and facing boil-off losses [100,101].

Compressed Hydrogen Storage

Compressed hydrogen is widely used in mobility, industry, and renewable integration. Storage vessels, often made from metals, polymers, and carbon fibre composites, support pressures up to 700 bar [102]. Key benefits include quick access, light weight, and high gravimetric energy density (33 kWh/kg), which supports decarbonization efforts [101].
However, compression consumes 13–18% of hydrogen's energy [101] and safety is a concern due to embrittlement from hydrogen diffusion into tank materials [102]. This requires advanced materials and protective coatings [101]. Despite these issues, CH_2

remains a technically mature solution, though high costs for advanced tanks still hinder widespread use [100,101].
To address limitations, research is focusing on stronger, lightweight materials, better pressure regulation, and system cost reductions [100].

Liquid Hydrogen Storage

LH_2 involves cooling hydrogen to -253°C to achieve liquid form. This method boasts high gravimetric energy density (2.7× that of gasoline) and is ideal for aerospace, heavy transport, and large-scale storage [100,103]. Storage typically occurs in double-walled, vacuum-insulated tanks [103].
The high volumetric density of LH_2 enables compact systems for long-range transport and high-energy applications [103]. Yet, liquefaction consumes up to 33% of hydrogen's energy, and boil-off losses remain significant, especially for near-term emergency use [101,104]. U.S. DOE targets 10% boil-off loss after 30 days [101].
Infrastructure for LH_2 is complex and costly. Cryogenic tanks require multilayer insulation and vacuum systems. Specialised handling systems and refuelling stations are needed, and materials must withstand thermal stress and hydrogen embrittlement [100,101].
Ongoing research focuses on enhancing liquefaction efficiency, developing better insulation, and creating hybrid systems combining LH_2 with other storage methods to reduce losses [100].

Table 17: Performance Metrics for compressed and liquid hydrogen

Metric/Property	Value per unit
Energy density	Compressed hydrogen achieves a volumetric energy density around 4–5 MJ/L. Its energy efficiency is reduced by ~13–18 % due to compression-related losses. Liquid hydrogen offers very high gravimetric energy density (~119 MJ/kg, LHV), but due to its low density, the volumetric energy density is only ~8–10 MJ/L, significantly lower than typical liquid fuels [105,106]
Transport/Logistics	Tube-trailer systems (MEGCs) typically consist of clusters of high-pressure cylinders arranged in modular trailers. Trailer length ranges from 6–16 m, able to carry up to ≈1 t H_2 [107]. Liquid hydrogen is transported in cryogenic tank-containers typically built to 40 ft ISO standard dimensions (≈ 12.2 m × 2.44 m × 2.59–2.55 m) [108]
Operational Robustness/ Durability	High-pressure hydrogen storage tanks offer reliable structural lifetime when properly designed and coated; however, hydrogen embrittlement remains the primary long-term degradation mechanism, especially in high-strength steels and aluminium liners, potentially leading to delayed cracking under stress [105]. Liquid hydrogen tanks operate under extreme cryogenic conditions (≈ –253 °C) where thermal stress combined with hydrogen diffusion can reduce ductility and lead to embrittlement, especially when valves or structural components warm and expose metal to hydrogen atoms [109]
Maintenance	Maintaining compressed hydrogen tanks involves regular inspections for hydrogen embrittlement, leak detection, and verifying structural integrity of high-pressure components such as valves, liners, and composite overwraps [110]. Maintenance of LH_2 cryogenic storage tanks requires rigorous monitoring of insulation integrity, boil-off rates, and self-pressurization behaviour, alongside regular leak and pressure-relief system checks to prevent hazardous failures [109]
Rapid, Intuitive and Safe Field Deployment	Compressed hydrogen systems, especially modular tube-trailer units or containerised Type III/IV cylinder banks, enable quick setup in emergency or remote locations. These preassembled racks (e.g. 20 ft or 40 ft container modules) can be transported by standard trucks or rail and connected rapidly with minimal onsite construction [111]Mobile liquid hydrogen systems like GenH2's LS20 deliver compact, self-contained liquefaction, storage, and dispensing in a trailer-mounted unit (~400 L) designed for plug-and-go operation in the field[112]
Training	Operators handling compressed hydrogen systems typically complete a one- to two-day training course, covering hydrogen properties, high-pressure gas safety, leak detection, system operation, and maintenance protocols [110]. Training for personnel working with liquid hydrogen typically extends to two to three days, given the added complexity of cryogenic operations, insulation systems, and boil-off management [110]
Acoustic Performance	Operational noise at hydrogen storage or fuelling facilities is primarily driven by compressors, vent lines, and cooling equipment. Typical sound pressure levels

	from compressors or electrolyser stackhouses at approximately 15 meters distance range between 56 and 63 dBA, with total site noise reaching around 68 dBA under worst-case conditions [110]
Circular Economy Principles	Compressed hydrogen tanks (Type I–IV): Most conventional tanks are made from thermosetting resin composites, which are difficult to recycle at end of life. Emerging efforts use thermoplastic liners or thermoplastic composite designs to enable recyclability through mechanical or chemical separation and recovery of fibres and matrix, supporting reuse and recycling strategies in line with circular-economy goals [113]. Liquid hydrogen tanks (cryogenic): Lifecycle assessment studies highlight that tank material choices (e.g. glass-fibre-reinforced polymer) significantly impact embodied CO_2, and eco-design approaches are recommended to reduce carbon footprint and facilitate end-of-life recycling or material recovery [114]
Safety	Compressed hydrogen: High-pressure gas (350–700 bar) poses risks of leaks, flammability, and hydrogen-induced embrittlement in steel vessels. To mitigate, materials selection (e.g. mid-strength steel, coatings), regular inspection, and venting protocols are essential components of safe design. Liquid hydrogen: Cryogenic tanks storing LH_2 (~–253 °C) bring added hazards—cold burns, asphyxiation risk from oxygen displacement, and flammable heavier-than-air gas clouds. Failure modes like BLEVE require specialised insulation, low-temperature tolerant materials and pressure-relief systems also designed to prevent hydrogen embrittlement in metal fittings [115]

II. Current Technological Development Trends/Development Trends & Market Analysis

Compressed hydrogen is gaining market traction in mobile and stationary applications due to efficiency improvements in compression and storage tank design (for providers see Table 18). Innovations like advanced composite pressure vessels are reducing weight and cost, while addressing safety concerns such as hydrogen embrittlement and material fatigue from cyclic loading [102,116]. The global compressed hydrogen market is expected to grow at a CAGR of 8.4% from 2025 to 2034, driven by regulatory support and clean energy demand [116].

Liquid hydrogen is expanding from aerospace into heavy transport and industrial sectors. While boil-off losses and liquefaction energy demands (~30% of energy content) remain challenges, research into better insulation, cold energy reuse, and superconducting transmission is underway [117,118]. The global LH_2 market is projected to reach USD 65.18 billion by 2030 [118].

Hydrogen Storage is a well-established research field. The top six patent holders include entities from Japan, France, and Germany, most notably BMW AG and Robert Bosch GmbH. While scientific activity stagnated between 2010 and 2020, the field has regained momentum over the past five years and is now once again prominently represented in the academic research landscape (see Annex 1).

Table 18: Global market key providers for Compressed and liquid hydrogen [116–119]

Company	Headquarters	Focus
Air Liquide	Paris, France	Compressed & Liquid H_2
Linde plc	Guildford, UK (legal: Dublin, IE)	Compressed & Liquid H_2
Air Products Inc.	Allentown, PA, USA	Liquid H_2 (mobility, industry)
Engie S.A.	Courbevoie, France	Compressed H_2
Cummins Inc.	Columbus, Indiana, USA	Liquid H_2 (via joint ventures)

III. Implications and Considerations for Emergency Response Organizations

Liquid hydrogen (LH_2) and compressed hydrogen (CH_2) are being considered as options in emergency preparedness, though infrastructure and handling remain barriers. Economic studies suggest LH_2 is more cost-effective than CH_2 for transport distances over 130–200 km and delivery volumes above 1 t, though these thresholds are model-based and may not directly reflect emergency deployment contexts. LH_2's volumetric energy density is significantly higher, making it preferable for large-scale deployments, while gaseous H_2 suits short-range logistics [117,120].

Modern LH_2 trailers hold 2,500–4,000 kg (up to 70 m³) at working pressures of 1–12.75 bar(a), relying on vacuum multilayer insulation. Key producers include Linde, Chart Industries, and Air Products [117]. Alternatives to LH_2 and CH_2 include metal hydrides, liquid organic hydrogen carriers (LOHCs), cryo-compressed hydrogen, and ammonia as a chemical carrier. These offer varied trade-offs between efficiency, cost, and infrastructure availability [121,122].

In emergency settings, compressed hydrogen is suitable for mobile units, fuel-cell-powered shelters, and rapid-response vehicles due to its fast refuelling and modular tank systems. Liquid hydrogen is more appropriate for long-duration operations like powering field hospitals, but requires cryogenic handling systems and trained personnel [117].

Operationally, both systems demand high safety standards. This includes reinforced tanks, leak detection, ventilation, and strict refuelling protocols. LH_2's low-temperature storage ($< -253\,°C$) introduces additional risks like thermal stress, embrittlement, and boil-off losses. Released LH_2 forms visible white vapor clouds; though highly flammable, extensive NASA and EU testing (PRESLHY) has shown that spontaneous ignition is rare under controlled conditions [117].

Hydrogen-based energy systems enable decentralised power generation via fuel cells or mobile electrolysis, improving resilience in disaster scenarios. Yet, infrastructure and cost remain barriers, especially for small-scale or remote responders.

3.1.7. Flow Batteries

Status:	Market available & in Research and Development
Key words:	Flow batteries, redox chemistry, long-duration storage, large scale storage

Summary

Flow Batteries provide a scalable and long-duration energy storage solution, primarily for stationary and grid-scale applications rather than rapid-deployment use. Their ability to supply stable power over extended periods without significant degradation addresses key challenges in energy resilience, particularly for emergency response operations. With modular and flexible deployment options, they may offer a practical alternative to conventional batteries and generators, enhancing sustainability while minimising safety risks. As advancements continue to improve efficiency and reduce costs, flow batteries are becoming an increasingly viable option for large-scale and mission-critical energy storage applications. However, their comparatively low energy density and large system size may limit portability in emergency contexts.

I. Technical Function and Description

Flow Batteries are electrochemical energy storage systems that store energy in liquid electrolytes circulating through an external storage system. Unlike conventional batteries, where the electrodes and electrolyte are sealed within a fixed cell, flow batteries separate power (determined by the cell stack) and energy (determined by the electrolyte volume), enabling flexible scaling [123,124].
Their basic structure consists of two tanks containing positively and negatively charged electrolyte solutions (catholyte and anolyte), which are pumped through an electrochemical cell stack during charge and discharge processes [123,125]. The redox-active species within the electrolytes undergo oxidation and reduction reactions, storing and releasing energy. The electrochemical reaction is reversible, allowing for repeated charge/discharge cycles with minimal degradation [126].
Within the cell stack, the electrolyte flows through porous electrodes, which enable surface reactions, while an ion-selective membrane separates the two half-cells, allowing specific ions to pass through to maintain charge balance [127,128]. Electrical current is produced by electron flow through an external circuit. The efficiency and lifetime of flow batteries depend significantly on membrane selectivity, electrode porosity, and electrolyte flow rate [129].
Flow battery technologies vary mainly by electrolyte chemistry. The most established is the Vanadium Redox Flow Battery (VRFB), which uses vanadium ions in multiple oxidation states. This avoids cross-contamination and supports a long cycle life (~15,000–20,000 cycles), though energy density is low compared to lithium-ion and vanadium is costly [124,129] (see Table 19). Zinc-Bromine Flow Batteries (ZBFB) provide higher energy density but require regular maintenance due to bromine volatility [130]-
Hydrogen electrolysers present a (Iron-Chromium, Hydrogen-Bromine, ORFBs) are under research but carry toxicity, cost, or stability issues that make them less relevant for near-term deployment [127,129]. Organic Redox Flow Batteries (ORFBs) offer tunability and potential sustainability but suffer from instability and degradation over longer cycles [131]. Membraneless Flow Batteries, which use immiscible liquids instead of ion-exchange membranes, reduce costs but at the expense of energy efficiency (~40–60%) [129]. Saltwater and Seawater Flow Batteries are in early research stages (TRL 2–

3) and show promise in sustainability, but current performance metrics are low [123,132,133].
Overall, flow batteries offer significant advantages for long-duration energy storage and grid integration of renewables due to their scalability, safety, and cycle stability. However, challenges remain in cost reduction, energy density, and materials optimization [127,128,130].

Table 19: Performance Metrics: Criteria for evaluating effectiveness

Metric/Property	Value
Power Output (W)	The power output of vanadium redox flow batteries varies significantly depending on the system scale. Laboratory-scale stacks typically deliver between 250 and 1200 watts, while commercial systems can achieve outputs of 1 megawatt or more, with some installations reaching up to 15 megawatts. Current research focuses on increasing power density, up to 0.8 W/cm^2, to enable more compact and efficient energy storage systems [134]
Transport/Logistics	Modular containerised designs support transport and plug-and-play installation. Yet, units are typically multi-ton and require cranes or heavy trucks, which reduces deployability for fast-response teams [135]
Operational Robustness/ Durability	Vanadium redox flow batteries demonstrate exceptional operational robustness, with cycle lives exceeding 10,000–20,000 cycles and calendar lifetimes of over 20 years. Their resilient aqueous electrolyte chemistry supports stable performance with minimal degradation and the ability to withstand full discharge and electrolyte mixing without long-term harm [136]
Maintenance	Flow batteries, especially vanadium-based systems, require comparatively low regular upkeep (monthly electrolyte checks and yearly inspections suffice for reliable operation). However, electrolyte rebalancing is required; this is a specialised task which may not be trivial for lightly trained personnel [137]
Rapid, intuitive, and safe field deployment	Vanadium flow batteries are increasingly deployed as modular, containerised systems that enable rapid, intuitive field installation (often requiring only a concrete pad and minimal onsite adjustments). Their non-flammable aqueous electrolytes and integrated safety features ensure secure and safe operation even under field conditions [136,138]
Training	While equipment vendors for vanadium flow batteries offer in-depth operator and maintenance training, publicly available sources don't specify exact durations. However, based on analogous utility battery training, programs generally last between 2 and 5 days [139]
Modularity and Microgrid use	Flow batteries, particularly vanadium and iron-based systems, offer highly modular architectures with independently scalable power and energy components, making them well-suited for microgrid applications. They have been successfully deployed in configurations ranging from hundreds of kilowatts to multiple megawatts, demonstrating flexible islanding capabilities and long-duration operation for resilience and renewable integration [140,141]
Acoustic Performance	Vanadium redox flow batteries emit very limited noise during operation, primarily from the circulation pumps, a moderate level requiring no special hearing protection under normal conditions [142]
Circular economy principles	Vanadium flow batteries exemplify strong alignment with circular economy principles through lifecycle strategies that emphasise reduced material use, reuse of electrolytes, and effective recycling of key components [143]
Safety	Redox-flow batteries are considered a safe energy storage technology due to their use of non-flammable aqueous electrolytes and the separation of energy and power components. Particularly vanadium-based systems have low toxicity and minimal fire or explosion risks. However, some chemistries such as bromine- or hydrogen-based systems require more stringent safety measures due to chemical volatility or gas formation [127,129]

II. Current Technological Development Trends/Development Trends & Market Analysis

The field of Flow Batteries is primarily driven by patent activity from China, followed by Japan and the United States (for product examples and providers see Table 20 & 21). Nonetheless, German organisations such as Reinz Dichtungs GmbH, Schaeffler Technologies GmbH, and the Fraunhofer Society also hold a notable number of patents. The substantial volume of scientific publications in recent years further indicates that the topic continues to be actively investigated within the research community (see Annex 1).

Table 20: Global market key providers for Flow-Batteries [144]

Market Leader	Headquarter	Focus
RedFlow Ltd	Australia	zinc-bromine flow batteries
Primus Power Corporation	USA	zinc-bromine flow batteries
VRB Energy	China	vanadium redox flow batteries (VRFBs)
Invinity Energy Systems Plc.	UK	vanadium redox flow batteries (VRFBs)
ESS Tech Inc.	USA	Develops iron flow batteries

Table 21: Examples for relevant products and Suppliers

Product	Seller	Link
Energy Warehouse: A fully-integrated, modular, and containerised iron flow battery for long-duration energy storage.	ESS Tech Inc.	Link
Invinity Vanadium Flow Batteries: Modular and scalable vanadium redox flow batteries, deployable in containerised units.	Invinity Energy Systems PLC	Link
E22's VCUBE: 50kW-250kmw energy storage system or	E22	Link
Salgenx Grid Scale 3000 kWh MegaWatt Pack Battery	Salgenx	Link
V-Flow M100- vanadium redox flow batteries, deployable in containerised units	V-Liquid	
FB 333-4 vanadium redox flow batteries, deployable in containerised units	Cell-Cube	Link
Customizable Energy Storage with Vanadium Redox Flow Battery Systems	sumitomoelectric	Link
Ever Flow Storage container VRFB from 5kwh 250kwh	SCHMID Group	Link
Volt Storage Iron Salt Battery	Volt Storage	Link
Storac small storage unit for domestic houses up tp 6 kwh	Prolux Solutions	Link

III. Implications and Considerations for Emergency Response Organizations

In emergency response settings, flow batteries, especially vanadium systems, could be relevant for semi-stationary field bases or reconstruction phases but are less suited for highly mobile operations due to weight and volume. Their non-flammable aqueous electrolytes are a clear advantage compared to lithium-ion. However, the need for pumps, tanks, and temperature control increases logistical demands, making them less intuitive for small teams or first-response scenarios. Despite their advantages, the systems' significant weight, size, and moving parts (pumps, electrolyte tanks) necessitate proper equipment handling, routine mechanical maintenance, and consideration of environmental factors such as temperature extremes, insulated enclosures or heating may be required in cold climates. Thus, flow batteries should be framed as complementary to lithium-ion or hydrogen systems, best suited for medium- to long-term deployments where transport logistics are manageable and uninterrupted power is critical [140,145].

3.1.8. Hydrogen Fuel Cells

Status:	Market available / in Research and Development
Key words:	H2

Summary

Hydrogen fuel cells are a clean energy technology that convert hydrogen into electricity with zero harmful emissions. Fuel cells have various applications, including stationary power generation, transportation and backup power systems. In the context of emergency response, their operational viability depends on the parallel availability of hydrogen supply chains (compressed or liquid), which are currently limited and logistically demanding. The Proton Exchange Membrane Fuel Cell (PEMFC) is the leading technology due to its efficiency and suitability for diverse sectors. However, high costs (especially for platinum catalysts and balance-of-plant components) and reliance on dedicated hydrogen infrastructure remain critical barriers. They are particularly suited for disaster relief scenarios, offering portable, reliable power for critical operations like medical facilities, emergency shelters, and communication networks.

I. Technical Function and Description

Hydrogen fuel cells are energy conversion systems that generate electricity from hydrogen through an electrochemical reaction, producing only water and heat as by-products. Unlike combustion-based systems, they operate without harmful emissions [146]. Their core components include an anode, a cathode, and an electrolyte membrane. Hydrogen introduced at the anode splits into protons and electrons. While the protons pass through the membrane, the electrons travel via an external circuit, creating electric current. At the cathode, protons, electrons, and oxygen combine to form water [147].

Fuel cells are widely used across various sectors including transportation, stationary power generation, and portable applications (see Table 22). They are classified based on operating temperature and electrolyte type into low-temperature (<250 °C) and high-temperature (>500 °C) categories [147].

The Proton Exchange Membrane Fuel Cell (PEMFC) operates at 60–80 °C and is known for quick start-up, low-temperature operation, and high-power density. It uses a solid polymer electrolyte and platinum-based catalysts, making it suitable for vehicles, portable generators, and emergency power systems (Mo et al. 2023; PowerUP 2024; [148].

The Solid Oxide Fuel Cell (SOFC) runs at 600–1000 °C with a solid ceramic electrolyte. It enables internal reforming of fuels and efficient heat usage, making it suitable for stationary power and combined heat and power (CHP) applications [147,149].

The Alkaline Fuel Cell (AFC) utilises an alkaline electrolyte like potassium hydroxide and operates at 90–100 °C. While highly efficient and used historically in aerospace (e.g., NASA missions), it is sensitive to CO_2 contamination [147].

The Phosphoric Acid Fuel Cell (PAFC) works at 150–200 °C using liquid phosphoric acid. It offers fuel flexibility and long durability, making it ideal for CHP and stationary applications [147,150].

The Molten Carbonate Fuel Cell (MCFC) operates at 600–700 °C using molten carbonate salts as electrolytes. It allows for internal reforming of fuels and high waste heat utilization, making it effective in industrial and large-scale stationary systems [147,151].

Each fuel cell type has distinct characteristics in terms of temperature, power range, efficiency, and application. For instance, PEMFCs cover 1–100 kW at 45–60% efficiency;

SOFCs range from 1 kW to 2 MW and exceed 60% efficiency. MCFCs reach up to 3 MW but require high temperature and stable materials [147,152].
Stationary applications span from micro-CHP systems to MW-scale grid-support installations. These include backup power, distributed generation, and remote off-grid supply. Demonstrator projects have validated such uses under real conditions [150,153].

Despite their potential, fuel cells face challenges such as catalyst degradation, sensitivity to impurities, and high manufacturing costs. However, continuous research and commercialization efforts aim to overcome these barriers and broaden deployment across emergency and industrial sectors [147,154,155].

Table 22: Performance Metrics for Hydrogen Fuel Cells

Metric/Property	Value
Power Output (W)	EM proton-exchange membrane fuel cells (PEMFCs) are typically commercialised in the range of 1 W to several kW, with micro-fuel cells for portable electronics often delivering under 5 W, while packaged systems for applications like backup power reach 1–5 kW, and larger stationary or transport fuel cell systems may scale up to tens or even hundreds of kilowatts [147,156].
Transport/Logistics	Portable hydrogen fuel cell generators such as the PowerUP UP1K has dimensions of approximately 700 × 222 × 410 mm and a total weight of 27 kg, making them easily transportable by a small team or vehicle (PowerUP 2024).
Operational Robustness/ Durability	Stationary SOFC systems typically demonstrate operational lifetimes exceeding 40,000 hours (approximately 5 years), with a target degradation rate of around 0.2% per 1,000 operating hours [157]. PEMFC systems can achieve up to 20,000 hours of operation under laboratory or pilot-scale conditions, and several thousand hours in automotive applications; however, degradation mechanisms such as catalyst corrosion limit their long-term stability [158].
Maintenance	PEMFC systems require regular monitoring and targeted maintenance, particularly to prevent membrane damage due to drying or flooding, as well as catalyst poisoning [159]. Stationary SOFC systems have higher maintenance demands on balance-of-plant components, stack replacement, and sealing elements; typical annual maintenance costs range between 2–5% of the initial capital investment, depending on system size and operating conditions [160].
Rapid, intuitive, and safe field deployment	Portable PEM fuel cell generators such as the PowerUP UP1K and UP3K feature a modular, plug-and-play design. These systems operate quietly and emission-free and have already been deployed in crisis scenarios such as emergency backup for 5G networks, mobile clinics, and military operations [161].
Training	No data available.
Modularity and Microgrid use	Modern fuel cell systems (e.g. PEMFC or SOFC) are designed to be modular and scalable, individual modules can be assembled into nano- or microgrids, enabling flexible distributed energy resources. They support both grid-connected and islanded operation, making them suitable for critical infrastructure such as telecoms or healthcare microgrids [162,163].
Acoustic Performance	Hydrogen PEM fuel cell systems (including those used in portable or stationary applications and vehicles) operate with very low noise and vibration levels. In some cases, the noise is reported to be up to 50% lower than that of comparable internal combustion engines, and overall PEM fuel cells exhibit minimal acoustic emissions even under dynamic conditions [164].
Circular economy principles	Recycling strategies applied to PEM fuel cells and electrolysers can reduce raw material demand, energy consumption and GHG emissions by up to ~20–60 %, with platinum recovery rates as high as 95 %, enabling a circular hydrogen economy based on design-for-recyclability and materials recovery[165]
Safety	Hydrogen fuel cell systems are generally considered safe when operated according to standards, but due to hydrogen's wide flammability range and low ignition energy, rigorous safety measures, such as leak detection, adequate ventilation, flame sensors, and material compatibility are essential to prevent fire or explosion risks [166].

II. Current Technological Development Trends/Development Trends & Market Analysis

The global fuel cell market is growing rapidly, with a projected increase from USD 8.89 billion in 2025 to over USD 34 billion by 2033, driven by rising demand in transportation and stationary power [167] (for product examples and providers see Table 23 & 24). PEM fuel cells dominate due to their compact size, low operating temperature (~80 °C), fast start-up, and high efficiency [151,167]. They are widely used in vehicles, data centres, UAVs, and aerospace [167]. Key markets include Asia-Pacific, Europe, and North America, where supportive policies and R&D drive adoption [152]. Despite high costs (mainly due to platinum catalysts) current R&D focuses on reducing platinum use and improving CO tolerance [147]. European manufacturers such as Bosch, Cummins, Nedstack, and Zepp Solutions offer PEM and SOFC systems for commercial use [149,168–170].

In contrast to many other technologies, this field is primarily driven by actors from the United States and Europe, particularly France and the Netherlands. Robert Bosch GmbH is also represented, ranking 14th among patent applicants.

The technology has been the subject of intensive research since the early 2000s, with a renewed peak in publication activity observed in 2024. The comparatively low number of patents relative to the volume of publications suggests that the field is still characterised by ongoing fundamental research rather than applied development (see Annex 1).

Table 23: Global market key providers for Hydrogen Fuel Cells [171]

Company	Headquarters	Thin-Film PV Focus
Ballard Power Systems	Canada/ USA	PEMFC
Bloom Energy	USA	SOFC
Plug Power	USA	PEMFC
Cummins / Accelera	USA (DE&NL)	PEMFC
Nedstack	NL	PEMFC

Table 24: Examples of products

Product	Seller	Link
Accelera	Cummins	[168]
PemGen CHP-FCPS, PEM Fuel Cell Stacks	Nedstack	[169]
SOFC-System	Bosch	[149]
Zepp.Y50, Zepp.X150	Zepp Solutions	[170]
UP-400, UP1K, UP3K, UPSystem, UPMObile, UPSystemMax	PowerUP Energy Technologies	[161]
EFOY 80, EFOY 150, EFOY Pro 900, EFOY Pro 1800, EFOY Pro 2800	SFC Energy (EFOY)	[148]
H2Genset	SFC Energy (H2Genset)	[172]
AIRCELL, BOXHY, THYTAN	H2SYS	[173]

III. Implications and Considerations for Emergency Response Organizations

Hydrogen fuel cells (HFCs) are increasingly recognised as a viable solution for emergency response operations due to their zero-emission operation, low noise output, and flexible deployment options. These systems can be applied in stationary roles (for example, supplying power to base camps from stored hydrogen) or as mobile units powering vehicles, field equipment, or portable systems used by response teams operating away from central infrastructure [154,167].

Various products reflect these use cases. For instance, the UP1K portable fuel cell generator by PowerUP Energy Technologies weighs only 27 kg and has compact dimensions, making it suitable for transport in standard vehicles and deployment in remote settings [161]. Meanwhile, stationary systems like the Bosch SOFC are scalable and suited for integration into critical infrastructure, though their logistics require truck-based transport due to size and weight [149]. The H_2Genset from SFC Energy AG offers a mobile, trailer-mounted power solution, allowing fast deployment to dynamic emergency environments [172].

From a logistical standpoint, small-scale HFCs can be transported manually or with light vehicles, while larger systems need heavy-duty logistics support [149,161]. The selection of fuel cell type and configuration depends on the desired power output, mobility, and the logistical capabilities of the deploying organization [150].

However, fuel cell systems also bring operational considerations. A key metric is energy conversion efficiency, especially when hydrogen is produced on-site from renewable sources, where initial conversion losses are high. Therefore, maximising the back-conversion efficiency in the fuel cell is critical [147]. Additional performance indicators include noise levels, pollutant emissions, fuel energy density, and the ease of fuel handling and transportation [154,167].

Regarding safety, the most critical issue lies in hydrogen storage and transport. Although HFCs themselves are inherently safe, the pressurised or cryogenic hydrogen they require must be handled with care [151].

3.1.9. Electrolysers Hydrogen

Status:	Market available / in Research and Development
Key words:	H2

Summary

use electricity to split water into hydrogen and oxygen, providing one pathway for low-emission hydrogen production depending on the electricity source. They can contribute to energy resilience by enabling on-site hydrogen generation, which may be relevant for fuel cells in emergency contexts. Proton Exchange Membrane (PEM) electrolysers offer high hydrogen purity, compact design, and fast response to power fluctuations, but are costly and depend on rare metals like platinum. Alkaline electrolysers are more affordable and durable for large-scale hydrogen production, though they respond more slowly and produce lower gas purity. Anion Exchange Membrane (AEM) electrolysers aim to cut costs using non-precious metals but still face challenges with membrane durability and efficiency. Solid Oxide Electrolysis Cells (SOECs) are efficient and can use industrial waste heat, but their high operating temperatures lead to material wear and system complexity, making durability and cost major challenges for broader use.

I. Technical Function and Description

Electrolysers split water into hydrogen and oxygen and are an important enabling technology for low-emission hydrogen production where renewable power is available. In emergency contexts, on-site electrolytic hydrogen systems can support resilient energy supply [174] (see Table 25).

There are four main types: PEM, Alkaline, AEM, and SOEC.

- **PEM (Proton Exchange Membrane)** electrolysers provide fast response, compact design, and high-purity hydrogen output. However, they are costly due to their use of precious metal catalysts like platinum and iridium [175,176].
- **Alkaline electrolysers** are more affordable and durable, making them suitable for large-scale hydrogen generation. Their drawbacks include slower response times and lower hydrogen purity [177–179].
- **AEM (Anion Exchange Membrane)** electrolysers aim to combine the advantages of PEM and alkaline systems, using non-precious metal catalysts. Challenges remain in membrane durability and efficiency [180,181].
- **SOEC (Solid Oxide Electrolysis Cells)** operate at high temperatures, achieving high efficiency and allowing use of industrial waste heat. However, the extreme heat leads to material degradation and system complexity, limiting durability and cost-effectiveness [119,182].

Key performance indicators of different Types

Table 25: Key performance indicators for PEM Electrolyte

Metric	PEM Electrolyte
System energy consumption (kWh/kg H_2)	50-83[183]
Transport/Logistics	Proton Exchange Membrane (PEM) electrolysers are available in both compact and containerised formats. For example, the Nel MC250 is a modular containerised unit with dimensions of approximately 12.2 × 2.5 × 3 meters, weighing around 30 tonnes [184]. The Quest One ME450, a 1 MW PEM plant, is housed in a standard 40-foot ISO container and weighs about 36 tonnes [185]

Operational Robustness/ Durability	PEM stacks achieve >40,000 hours of operation, with degradation rates ~4–5 mV per 1,000 h[186]
Maintenance	PEM stacks generally need replacement after 40,000–60,000 h [187]; Balance of plant components require inspection and upkeep per OEM guidance.
Rapid intuitive and safe field deployment	Containerised PEM units (like Nel MC250) allow fast deployment and safe operation without handling caustic substances [184,188]
Training	Operators require specific training to safely and effectively use PEM electrolysers, typically lasting 2–3 days and covering safety, operation, Balance of plant systems, and maintenance [189]
Modularity and Microgrid use	Containerised PEM solutions are modular and can quickly adjust load, making them suitable for renewable-integrated microgrids [184,190]
Acoustic performance	Containerised PEM electrolysers are relatively quiet, producing noise levels between 60–83 dB(A) at 1 m. Full-scale industrial installations may require acoustic enclosures or sufficient clearance to comply with noise regulations [191–193]
Circular economy principles	Research and industry efforts are exploring options for improving circularity, including recovery and reuse of critical materials to reduce supply risks, emissions, and costs while enabling sustainable scale adoption [165,194]
Safety	Containerised PEM electrolysers are engineered with multi-layered safety systems, including gas leak detection, overpressure protection, and emergency shutdown procedures, to minimise hydrogen-related hazards such as flammability, explosion risk, and gas accumulation in enclosed spaces. These risks stem from hydrogen's low ignition energy, wide flammability range (4–75 %), and tendency to rise and accumulate near ceilings if not properly ventilated [195,196]

Table 26: Key performance indicators for Alkaline Electrolyzers

Metric	Alkaline Electrolysers
Energy consumption (kWh/kg H_2)	50-78 [183]
Transport/Logistics	Alkaline electrolysers range from small bench research units, like the subcooled gaseous hydrogen 2 kW stack (256 × 327 × 190 mm, 50 kg) ideal for lab use [197], to skid-mounted industrial systems offering outputs of ~10 Nm³/h, such as the PERIC CNDQ-10 (1.355 × 0.85 × 0.78 m, 1 750 kg) [198]. McLyzer 800-30 is a large-scale industrial module, container-compatible (9.5 t), delivering high-output [199]
Operational Robustness/ Durability	Alkaline water electrolysers are robust and durable under stable conditions and large-scale operation, but maintaining their longevity under dynamic, real-world renewable energy integration requires ongoing innovations in materials, system design, and operation strategies.[200,201]
Maintenance	Alkaline water electrolysers (AWEs) are relatively low-maintenance compared to other technologies such as PEM or SOEC, especially when operated under continuous, stable conditions. However, maintenance demands increase significantly under dynamic operation (e.g., coupling with solar or wind power), mainly due to electrode degradation, gas crossover, and electrolyte deterioration [200,202]
Rapid intuitive and safe field deployment	Alkaline electrolysers are suited for rapid and safe deployment due to their technological simplicity and modularity, making them suitable for decentralised or emergency hydrogen applications [174,203].They have however a slow start-up [204]
Training	Alkaline electrolysers are relatively easy to operate, requiring only basic technical training and safety awareness. More in-depth training is needed for maintenance and troubleshooting, but modular design and intuitive interfaces help lower the learning curve [179,203] [174,179,205][174,179,205][175,180,206]
Modularity and Microgrid use	Alkaline water electrolysers, through their modular design and compatibility with intermittent renewables, are suitable for microgrid applications [176,203,205]
Acoustic performance	Alkaline water electrolysers themselves are not loud, and overall system noise is usually minimal and dominated by auxiliary components. With proper design, AWEs are suitable for urban, residential, or mobile use where low acoustic impact is essential [206,207]
Circular economy principles	Alkaline water electrolysers embody circular economy principles through their use of abundant materials, repairability, long service life, recyclability, and role in renewable energy storage and sector integration [203,208]
Safety	Alkaline water electrolysers are generally safe when properly operated, though they involve risks from handling caustic potassium hydroxide (KOH) and flammable hydrogen gas. Hazards include chemical burns, gas crossover, and overpressure, but modern systems mitigate these through safety features like pressure relief valves, hydrogen detectors, and automatic shutdown mechanisms [203,209]

Table 27: Key performance indicators for AEM (Anion Exchange Membrane)

Metric	AEM (Anion Exchange Membrane)
Energy consumption (kWh/kg H_2)	57-69 [183]
Transport/Logistics	AEM electrolysers offer transportability due to their modular design, with single units such as the Enapter EL 4 weighing approximately 42 kg and megawatt-scale AEM Multicore systems delivered in standard 40-foot containers. Their pre-configured format enables rapid deployment and flexible integration, particularly in decentralised and off-grid energy systems [210,211]
Operational Robustness/ Durability	AEM electrolysers have made significant progress in operational durability, with modern membranes demonstrating over 1,000 hours of stable performance and even year-long operation with minimal degradation. While still in development, these advances suggest a strong potential [212,213]
Maintenance	AEM electrolysers are still an emerging technology under active development, but recent studies show that they can achieve stable operation for over a year under optimised conditions. While full industrial readiness has not yet been reached, advanced membrane materials and improved electrode designs suggest strong potential for low-maintenance, durable performance in the near future [212,214]
Rapid intuitive and safe field deployment	AEM electrolysers, such as those from Enapter and Hygreen, are optimised for field deployment: they offer plug-and-play installation within minutes. These systems also integrate robust safety and stability features [215,216]
Training	Current publicly available sources do not specify an exact number of training days required for AEM electrolyser operation. However, vendors like Enapter report several days of hands-on training, and analogous PEM electrolysis training courses typically last around three days, indicating that practical operation training likely requires a comparable multi-day program [189,217]
Modularity and Microgrid use	AEM electrolysers from suppliers like Enapter are modular and designed for microgrid integration, enabling rapid plug-and-play deployment within existing renewable systems. Their containerised or compact form factors and stack-level scalability ensure flexibility in microgrid applications [205,218]
Acoustic performance	AEM electrolysers typically emit sound levels ranging from below 80 dB(A) during standard operations up to around 85 dB(A) at a 1 m distance, with occasional brief peaks (e.g., during purging). These noise levels require appropriate hearing protection and ventilation measures to ensure safe occupational exposure [219,220]
Circular economy principles	AEM electrolyser manufacturers like Enapter integrate circular economy principles by implementing structured take-back programs and conducting life-cycle analyses to recover and recycle critical components [221]
Safety	AEM electrolyser operation carries inherent risks—including hydrogen leakage, potential explosion from H_2/O_2 mixtures, electrical shocks, and alkaline chemical exposure—which are mitigated by intrinsic safety systems (e.g., self-pressurization, leak detection, automatic shutdown), robust ventilation, and personal protective equipment. Compliance with standards like IEC 60079-10-1 and implementation of hydrogen sensors, pressure/temperature monitoring, and operator training are essential to ensure safe operation [222,223]

Table 28: Key performance indicators for SOEC (Solid Oxide Electrolysis Cells)

Metric	SOEC (Solid Oxide Electrolysis Cells)
Energy consumption (kWh/kg H_2)	38-48 [183]
Transport/Logistics	SOEC modules are transported as heavy, skid-mounted systems, with standardised industrial dimensions (e.g., ~1.4 × 1.9 × 1.7 m for 250 kW stack units) to facilitate forklift and container handling. Although specific weights are not publicly disclosed, the design emphasises modular skid logistics suitable for road and site delivery [224,225]
Operational Robustness/ Durability	SOEC systems exhibit robust operational performance, with typical stack lifespans ranging from 4 years (Sunfire Gen 3) up to 7–9 years based on SOFC analogues, and demonstrate stable long-term voltage degradation rates of 10–25 mV per 1,000 hours [183,226]
Maintenance	SOEC systems follow structured maintenance cycles, including stack replacements every 4–7 years and BoP servicing at 10–12 years [183,227].
Rapid intuitive and safe field deployment	SOEC systems, such as Sunfire's pre-assembled HyLink Gen 3 modules, allow for field deployment within a few weeks [225]
Training	There is no publicly available information detailing how long new operators need to be trained on SOEC systems
Modularity and Microgrid use	SOEC technology is modular, with systems designed for scalable deployment that can be integrated into microgrid configurations. Academic and industrial demonstrations confirm successful microgrid applications that use modular SOEC [228,229]
Acoustic performance	There is no published information on the acoustic performance or noise levels of SOEC systems

Circular economy principles	Recent studies show that SOEC stacks can be effectively recycled using hydrometallurgical leaching, recovering over 89% of critical metals and rare earth elements for reuse in new devices, enabling a circular material cycle [230,231]
Safety	SOEC systems incorporate multiple safety controls: robust ventilation and hot-box architecture to mitigate ignition hazards, operator training, and automated fault-detection for safe shutdowns [232,233].

II. Current Technological Development Trends/Development Trends & Market Analysis

The global electrolyser market is rapidly expanding, driven by the demand for green hydrogen (for product examples and providers see Table 29 & 30). Proton Exchange Membrane (PEM) electrolysers are gaining traction due to their high efficiency, fast response times, and low maintenance, reaching USD 8.10 billion in 2025 and projected to grow to USD 15.06 billion by 2034 [234]. Alkaline electrolysers remain competitive with their durability and lower costs, particularly in large-scale industrial applications, and are expected to reach USD 217.36 million by 2032 [235]. Anion Exchange Membrane (AEM) electrolysers offer promise due to cost-effective materials and rapid growth (CAGR 97.7%), although commercialization remains in early stages [236]. Solid Oxide Electrolysis Cells (SOECs) stand out for high efficiency at elevated temperatures (500–850 °C) and are projected to grow from USD 517.06 million (2025) to USD 5.37 billion (2030), supported by EU initiatives and companies like Sunfire, Elcogen, and Topsoe [232,237].
With respect to patent analysis and research, Europe is strongly represented in this topic. In particular, the German companies *Robert Bosch GmbH*, *Linde GmbH*, and *Siemens Energy Global GmbH & Co. KG* are among the patent leaders. Research-wise, an exponential growth is emerging, which suggests further significant research expenditures in the coming years (see Annex 1).

Table 29: Global market key providers for Electrolysers

Company	Headquarters	Electrolyser Technology
Nel ASA	Norway	Alkaline, PEM [238]
Siemens Energy	Germany	PEM [239]
Plug Power	USA	PEM[240]
ITM Power	UK	PEM [241]
Thyssen Krupp	Germany	Alkaline [241]

Table 30: Examples for related products

Product	Seller	Link
PSM Series PEM Electrolyser	Nel Hydrogen (Norway)	Link
A Series Atmospheric Alkaline Electrolyser	Nel Hydrogen (Norway)	Link
Titan EZ-Series PEM Stack	Fuel Cell Store (USA)	Link
Quest One ME450 PEM Electrolyser (1 MW)	Quest One (Spain)	Link
IMI VIVO PEM Electrolyser	IMI Critical (UK)	Link
Accelera PEM Electrolyser System	Accelera	Link
Ohmium PEM Cabinet System	Ohmium Technologies	Link

III. Implications and Considerations for Emergency Response Organizations

Hydrogen electrolysers could contribute to decentralised energy provision for emergency response organizations, depending on local power supply and logistics. Among the main technologies - PEM, Alkaline (AEL), Anion Exchange Membrane (AEM), and Solid Oxide Electrolysis Cells (SOEC) - each offers distinct logistical and operational profiles critical to disaster deployment.

PEM electrolysers are currently the most commonly considered option for field deployment, as they combine compact size, rapid start-up, and high-purity output. Commercial systems like those by Plug Power and Nel Hydrogen are available in mobile or containerised configurations, enabling fast installation and integration with renewable power sources in remote or damaged areas [184,240].

AEL systems, while cost-effective and durable, are bulkier and use caustic electrolytes (e.g., KOH), which pose logistical and safety risks in disaster zones. Their slower dynamic response and handling requirements make them less ideal for rapid, mobile deployment, though they remain relevant for longer-term, centralised operations [242].

AEM electrolysers are emerging as a potentially flexible and lower-cost option, though their long-term performance is less established. Companies like Enapter have developed lightweight systems tailored for disaster response, combining low-cost, non-precious materials with fast deployment and compatibility with renewable sources [243].

SOEC systems provide high efficiency, especially when integrated with waste heat recovery, but their high-temperature operation (500–850 °C) limits their mobility and response time. They are better suited to centralised hydrogen production with subsequent distribution to crisis areas [232].

From a logistics perspective, PEM and AEM systems are most appropriate for mobile and off-grid setups. Operational success depends on integration with existing energy systems, environmental resilience, and personnel training in handling and maintenance [244].

Safety is paramount: all electrolysers produce reactive gases like hydrogen and oxygen, and some (e.g., AEL) involve hazardous liquids. Proper ventilation, pressure control, and emergency shutdown systems are vital to mitigate risks [176].

In conclusion, PEM and AEM technologies appear most relevant for rapid hydrogen-based energy support in disaster scenarios, although practical feasibility depends on training, logistics, and integration with local infrastructure.

3.1.10. Micro Gas Turbines

Status:	Market available
Key words:	Micro Gas Turbine, CHP, Distributed Generation, Hydrogen Combustion, Biogas, Syngas, Power-to-Power (P2P)

Summary

Micro Gas Turbines (MGTs) are compact, fuel-flexible energy systems that enable combined heat and power (CHP) generation. Their decentralised applicability, relatively fast start-up, and compatibility with multiple fuels position them as a potential option for off-grid and emergency operations.

I. Technical Function and Description

Micro Gas Turbines (MGTs) are small-scale combustion turbines designed for efficient and sustainable energy generation. They operate on the Brayton cycle, a thermodynamic process that involves compressing ambient air, mixing it with fuel, and igniting it to produce high-temperature, high-pressure gases. These gases then expand through a radial single-stage turbine, generating mechanical energy that is converted into electricity. Many MGTs incorporate a recuperator, a heat exchanger that improves efficiency by recovering exhaust heat and using it to preheat incoming compressed air. Due to their compact size and modular design, MGTs are particularly well-suited for distributed energy applications, enabling their deployment in microgrids, industrial facilities, and remote locations where conventional large-scale power plants are impractical [245,246] (see Table 31).
Their capability to operate on multiple fuels, including natural gas, biogas, hydrogen, and syngas, provides flexibility in energy sourcing and contributes to carbon reduction efforts. MGTs also play a crucial role in combined heat and power (CHP) systems, where the waste heat produced during electricity generation is captured and repurposed for heating or industrial processes, significantly improving overall energy utilization [247,248].
MGTs can be combined with Power-to-Power (P2P) concepts, where renewable energy is converted into hydrogen and later used in gas turbines, though integration remains at pilot and demonstration stages. This capability enhances grid stability and enables long-term renewable energy storage, addressing one of the key challenges of intermittent renewable sources such as wind and solar [249]. Their relatively fast start-up and extended maintenance intervals may support use in decentralised or remote applications, including potential relevance for emergency response [247,248].

Table 31: Performance Metrics for Micro Gas Turbines

Metric/Property	Value per Module
Power Output (W)	25,000 W – 500,000 W [245,250]
Transport/Logistics	Transportable via truck, cargo aircraft, or shipping container; modular containerised systems allow rapid deployment even in remote locations [249,251]
Operational Robustness/ Durability	Designed for remote, harsh conditions. Withstands temperature extremes and rough terrains [247,252]
Maintenance	Long maintenance intervals (>10,000 hours); low maintenance needs due to simple architecture and fewer moving parts [245,252]
Rapid, intuitive, and safe field deployment	Quick setup (within hours to few days); Requires minimal infrastructure and training [247,248]
Training	Automated systems reduce training needs. Usable by lightly trained personnel [248,250]

Modularity and Microgrid use	Fully compatible with microgrids; can integrate with hybrid renewable systems (solar, hydrogen storage, fuel cells) [249,250]
Acoustic Performance	Low-noise operation, suitable for deployment near sensitive infrastructure (e.g. living quarters) [247]
Circular economy principles	Modular design supports recycling of high-performance alloys; increasing focus on sustainable sourcing and recycling of materials [253]
Safety	Low-pressure operation minimises explosion risk; compliant with NOx/CO_2 emission regulations; safe autonomous shutdown systems included [247–250]

II. Current Technological Development Trends/Development Trends & Market Analysis

The continuous advancement of MGT technology is focused on increasing efficiency, fuel flexibility, and integration with renewable energy sources. One key trend is the use of hydrogen and ammonia as alternative fuels, reducing carbon emissions while maintaining high combustion efficiency [247,248]. Additionally, the integration of advanced recuperators significantly enhances thermal efficiency by utilising exhaust heat to preheat incoming air, reducing fuel consumption [247]. Hybridization with batteries and fuel cells is another significant trend, allowing MGTs to operate alongside renewable energy sources such as solar and wind to provide stable and reliable power generation [247,250].

Additionally, advancements in thermodynamic modelling and exergy optimization have further improved the efficiency and sustainability of MGT-based energy systems, reducing fuel consumption and increasing energy output [251].

The introduction of AI-driven digital twins and predictive maintenance technologies has also contributed to improving MGT performance, optimising maintenance schedules, and reducing operational downtime [251,253].

Micro gas turbines (MGTs) are undergoing rapid advancement to meet modern distributed energy needs. Recent literature highlights notable thermodynamic efficiency improvements: while a basic microturbine Brayton cycle yields low electrical efficiency (~17%), recuperated designs now achieve around 30% electrical efficiency [245]. In combined heat-and-power (CHP) mode, overall energy efficiency can approach 90% by utilising exhaust heat for useful thermal output [245]. Ongoing R&D is implementing regenerative cycles, intercooling, vapor injection, and advanced materials to further boost performance and narrow the efficiency gap with larger engines [254]. MGTs are also valued for their fuel flexibility, operating on natural gas, biogas, liquid fuels and increasingly on carbon-free fuels like hydrogen and ammonia [255]. Switching from methane to ammonia in an MGT has been shown to incur only a minimal drop in electric efficiency (~0.5 percentage points) while maintaining high total efficiency (~75–79% in CHP mode) [255], enabling near-zero-carbon generation. Burning hydrogen or ammonia does require combustion system innovations to manage flame speed, autoignition, and NO_x emissions, but recent demonstrations of stable ammonia/hydrogen-fuelled microturbine operation (with combustion efficiencies ~89–96%) and strategies like fuel blending or humidification underscore the progress in this area [255]. Another trend is the hybridization of MGTs with renewables and storage technologies. MGTs are being integrated into microgrids alongside solar fields, biomass gasifiers, Organic Rankine Cycle units, fuel cells, and batteries to create self-sustaining hybrid energy systems [254]. Such configurations exploit MGTs' quick ramp-up and dispatchability to stabilise intermittent solar/wind output [245], while using renewable heat or fuels to displace a portion of the fossil fuel input, thereby improving efficiency and reducing emissions [254]. For example, solar-boosted microturbine setups can use concentrated solar thermal energy to preheat air, cutting fuel consumption, and include thermal storage to maintain power output after sundown [254]. Likewise, coupling MGTs with high-temperature fuel cells (e.g. SOFC-MGT hybrids) allows the turbine to generate extra power from the fuel cell's hot exhaust, markedly increasing overall electrical efficiency [254]. In parallel, the digitalization of MGT operations is enhancing reliability and economics. AI-based predictive maintenance and fleet monitoring systems have been

deployed to perform real-time condition diagnostics, which reduces unscheduled downtime, lowers O&M costs and extends component life [256]. Data-driven models and digital twins are used to predict faults and optimise performance across multiple units, facilitating proactive maintenance scheduling and optimal dispatch in smart grids [251,253]. Regarding cost and market development, micro gas turbines are steadily gaining traction worldwide as technology matures. They feature relatively low maintenance needs and the potential for low-cost mass production, giving them a competitive edge in distributed generation [245]. The global MGT market has been expanding at roughly 9% annually and is projected to reach around $350–360 million by the mid-2020s, reflecting growing adoption driven by their versatility, efficiency and compatibility with clean energy goals [247]. MGTs are capturing a larger share of the small-scale CHP sector. For instance, their share in sub-1 MW CHP installations climbed from ~17% to ~30% over the past decade as they increasingly compete with reciprocating engines in commercial and industrial onsite generation [247].
A related concept is the free-piston engine, which also converts chemical energy from combustion into mechanical or electrical energy. Unlike conventional engines with a crankshaft, it uses a freely moving piston whose linear motion drives a linear generator or compressor. Although several prototypes have demonstrated high efficiency and fuel flexibility (e.g., diesel, natural gas, hydrogen), the technology is still at a pre-commercial stage, with ongoing research focusing on durability, control systems, and integration into hybrid power units.
In terms of application-oriented development, the field of micro gas turbines is primarily driven by China and the United States (for product examples and providers see Table 32 & 33). Within Europe, however, Germany plays a leading role, with key contributions from General Electric Technology GmbH, Siemens, and the German Aerospace Center (DLR). Research activity in this area has stagnated in recent years, with approximately 200 scientific publications per year (see Annex 1).

Table 32: Global market key providers for Micro Gas Turbines [257–259]

Company	Headquarters (Country)
Capstone Green Energy Corporation	USA
Bladon Technologies Limited	United Kingdom
Aurelia Turbines	Finland
FlexEnergy Solutions	USA
Micro Turbine Technology	Netherlands
TurboTech Precision Engineering	India
Ansaldo Energia	Italia
OPRA Turbines / Destinus Energy	Netherlands

Table 33: Examples for related products

Product	Seller	Link
Capstone C65 Microturbine	Capstone Green Energy Corporation	Link
Aurelia® iA400	Aurelia Turbines	Link
Ansaldo AE-T100	Ansaldo Energia	Link
Bladon MTG12	Bladon Technologies Limited	Link
FlexEnergy GT333S	FlexEnergy Solutions	Link
OPRA OP16	OPRA Turbines / Destinus Energy	Link
FusionFlight ARC	FusionFlight	Link

III. Implications and Considerations for Emergency Response Organizations

MGTs can provide decentralised power generation that may be deployed via truck, cargo plane, or containerised module, offering potential relevance for emergency contexts. Their small footprint and automated operation enable fast installation within hours, with minimal training required for field personnel [247,248]. In disaster response scenarios (such as earthquakes, floods, or military operations) MGTs can power field hospitals, mobile command centres, and water purification systems. The ability to operate on local fuels such as biogas or syngas increases deployment flexibility in crisis regions with limited fuel infrastructure. Moreover, their modular architecture allows for scalable power provisioning tailored to specific needs, from small remote outposts to large emergency shelters. In hybrid setups, MGTs paired with batteries ensure continuous operation during load peaks or intermittent fuel supply. Real-time diagnostics and predictive maintenance systems reduce the need for on-site technicians, enhancing uptime and reducing risk during prolonged emergencies [249,251]. Compared to diesel generators, MGTs produce lower emissions and noise levels, supporting safer and more sustainable humanitarian missions. Compliance with emissions standards and cybersecurity protocols enables safe use even in sensitive environments such as hospitals or conflict zones; however, additional organisational restrictions or protective rules for handling gas and other hazardous materials may still apply and will need to be addressed through updated regulations and operational guidelines [253,260].

3.1.11. Biomass and Waste-to-Energy

Status:	Market-available & R&D
Key words:	Biomass; Waste-to-Energy; Biogas; Gasification; Anaerobic Digestion; Pyrolysis

Summary

Biomass and Waste-to-Energy technologies use organic matter, such as agricultural residues, forest waste, or municipal solid waste, to produce energy in the form of heat and electricity. Depending on the feedstock and process, methods include direct combustion, gasification, and anaerobic digestion. These technologies **may** support decentralised energy supply in rural or off-grid contexts, subject to feedstock availability, logistics, and site conditions. Key considerations include feedstock logistics, emissions control, system complexity, and variability in energy output.

I. Technical Function and Description

Biomass and Waste-to-Energy (WtE) technologies include direct combustion, gasification, and anaerobic digestion. For mobile and emergency-oriented use, small-scale gasification is particularly promising due to its compactness, efficiency, and fuel flexibility.

Gasification systems convert solid biomass into a combustible synthesis gas (syngas) through partial oxidation under controlled high temperatures. This syngas, mainly consisting of CO, H_2, and CH_4, can power internal combustion engines or microturbines for electricity generation. Containerised systems (~50–500 kW) are available on the market; actual deployability in emergency field conditions depends on site access, permitting, and operator capacity [261,262] (see Table 34). These units can reach electrical efficiencies up to 30–35%, and total system efficiencies over 80% in Combined Heat and Power (CHP) configurations [262,263].

A typical small-scale biomass gasification unit includes: (1) pre-treatment modules for drying and feedstock sizing, (2) a gasifier (often fixed-bed), (3) gas cleaning units to remove tar and particulates, and (4) an energy conversion module. Systems designed for deployment in emergency scenarios are modular and transportable, some models are EU-pallet compatible and operable off-grid [264].

Field use imposes specific technical demands: syngas quality must remain stable; cleaning systems must be efficient; and systems must tolerate variable feedstocks such as chipped wood, pellets, or organic waste [263,265]. New hybrid approaches, like coupling gasifiers with solid oxide fuel cells (SOFCs), show potential for reaching >50% electric efficiency in compact units [261]. However, system reliability still depends heavily on trained operators, consistent fuel properties, and maintenance of gas cleaning systems [262,266].

Table 34: Performance Metrics for Biomass and Waste-to-Energy Systems

Metric/Property	Anaerobic Digester (≈ 20 kW_e)
Power Output (W)	50–500 kW (electric); higher for heat in CHP setups [262,263]
Transport/Logistics	Modular containerised or pallet-mounted systems; truck-portable [262,264,267]
Operational Robustness/Durability	Robust against fuel variation; suitable for remote conditions [262,265,266]
Maintenance	Daily filter and ash removal; moderate complexity [263,266]
Rapid, Intuitive and Safe Field Deployment	Possible within <24 h for certain commercial units; depends on site readiness, permits, and operator availability [264,267]
Training	Requires safety and technical training; operation manuals essential [263,264,266]
Modularity and Microgrid use	Modular architecture; compatible with microgrids [262,265]
Acoustic Performance	Moderate noise levels; quieter than diesel generators [265]
Circular Economy Principles	Converts waste to energy; enables local resource use and waste mitigation [261,268]
Safety	Safe if operated correctly; risks include syngas handling and tar formation [263,264,266]

II. Current Technological Development Trends/Development Trends & Market Analysis

Development of small-scale WtE technologies is driven by policy shifts toward decarbonization, energy independence, and circular economy principles. Modular gasification units are being positioned for microgrid/off-grid use; their relevance for emergency contexts should be confirmed through deployment trials. These systems benefit from declining component costs, digital monitoring advances, and increased demand for energy autonomy in climate-vulnerable and remote regions [261,264](for product examples and providers see Table 35 & 36).

The integration SOFCs, advanced gas cleaning systems, and automated feed mechanisms mark key technological trends. Manufacturers are working to simplify interfaces and reduce required setup times, which is crucial for emergency and mobile use cases. EU and international support schemes have spurred investments in low-emission bioenergy and modular WtE innovations [265].

Field-oriented research emphasises container-based units with 50–500 kW outputs, able to operate on heterogeneous feedstocks. Pilot and development projects have been reported in multiple regions, including parts of Asia and sub-Saharan Africa; scope and outcomes vary by program. However, challenges remain in standardising technologies, ensuring fuel supply logistics, and training personnel [262,263].

Private-sector uptake is growing in sectors such as defence, humanitarian aid, and off-grid telecom infrastructure. Modular biomass WtE systems are increasingly tested in pilot programs under real-world conditions, including coastal resilience hubs and mobile hospitals [267,268]. The commercial market, while fragmented, is evolving toward interoperable, multi-purpose units that combine energy provision with waste mitigation.

The field of biomass and waste-to-energy encompasses a broad range of technologies, which is reflected in the high volume of both scientific publications and patent filings. From a research perspective, activity in this area appears to be approaching saturation; however, with approximately 8,000 publications annually, it remains a highly visible topic within the scientific community.

In terms of patent activity, China is the dominant actor, followed primarily by the Danish company Novozymes Inc. and the French research institute IFP Energies Nouvelles. In Germany, BASF SE holds the highest number of active patents in this field, with a total of 81 (see Annex 1).

Table 35: Global market key providers for Biomass & Waste-to-Energy

Company	Headquarters (Country)
Eco Waste	Israel
Terragon Environmental Technologies	Mexiko
All Power Labs	USA
SEaB Energy	UK
Ankur Scientific	India
PyroGenesis	Canada

Table 36: Examples for related products

Product	Seller	Link
PUXIN Portable Assembly Biogas System	Alibaba	Link
MAGS^{TM}	Terragon	Link
HomeBiogas 2	HomeBiogas	Link
Community Power Corporation	BioMax Units	
Flexi Biogas Systems	T-Rex biogas plants	Link
Power Pallet - PP20	All Power Labs	Link

III. Implications and Considerations for Emergency Response Organizations

Small-scale biomass WtE units offer practical energy solutions for disaster relief and emergency operations, particularly where fuel logistics, infrastructure damage, or waste accumulation are challenges. Systems under 500 kW can be truck-mounted or containerised, enabling fast deployment. They can convert local biomass or biodegradable waste into reliable electricity and thermal energy [262,263].
Potential use cases include field hospitals, command posts, communications, and medical refrigeration, subject to validated uptime, emissions control, and operator capacity. Some units also support hybrid use, e.g. co-producing desalinated water or biochar, enhancing their utility in resource-scarce settings [269]. WtE may reduce diesel runtime and emissions and manage local waste streams, where fuel preparation, emissions control, and logistics are in place.
However, risks include syngas leakage, tar buildup, and inconsistent energy output with poor fuel quality. Emergency responders must be trained in operational safety, basic troubleshooting, and system startup protocols [263,264,266]. Units typically require daily maintenance: ash removal, filter checks, and system calibration. Remote monitoring and diagnostics can reduce on-site technician needs, though internet connectivity is a limiting factor in some zones [266].
For WtE multi-fuel flexibility is essential. Systems should accept wood chips, agricultural residues, and sorted organic waste, ensuring fuel availability in crisis settings [264,265]. Manufacturers have started offering solutions optimised for humanitarian and off-grid contexts, with setup times under 24 hours and plug-in compatibility with microgrid architectures [267].
Overall, biomass WtE appears more suitable for mid- to long-term operations than for immediate first response, pending validation of logistics, emissions control, and staffing. When planned with logistics, fuel access, and training in mind, these systems provide climate-resilient, self-sufficient energy solutions for emergency contexts [261–263,268].

3.1.12. Methanol-Based Energy Systems

Status:	Prototype and early commercial stage; proven performance in field tests and research pilots for portable and off-grid use
Key words:	Methanol, fuel cell, DMFC, synthetic fuels

Summary

Methanol-based energy systems may offer a compact and efficient solution for off-grid and emergency power needs. Utilising Direct Methanol Fuel Cells (DMFCs), these systems convert liquid methanol into electricity through a low-temperature electrochemical process. Features such as modularity, passive operation, and simplified maintenance may support rapid deployment, but field validation is still needed.

I. Technical Function and Description

Methanol-based energy systems use Direct Methanol Fuel Cells (DMFCs) to convert methanol and oxygen into electricity, heat, and water through an electrochemical process. Unlike hydrogen fuel cells, DMFCs use liquid methanol, simplifying logistics and storage for field operations. At the anode, methanol undergoes oxidation, producing electrons, protons, and carbon dioxide. Electrons pass through an external circuit to deliver power, while protons cross a proton exchange membrane to recombine with oxygen at the cathode to form water [270,271].

One of the most attractive features of DMFCs is their ability to operate at relatively low temperatures (typically 60–90 °C), allowing the use of lightweight and cost-effective materials and avoiding complex thermal management systems [270,272] (see Table 37). This makes them potentially suitable for off-grid or emergency contexts, pending validation of logistics and durability.

Advanced system designs emphasise the integration of passive airflow configurations that eliminate the need for fans and compressors. This passive design not only reduces power consumption but also enhances reliability and portability, aligning with the requirements for mobile energy systems [273]. Novel architectures such as air-breathing stacks, reduced catalyst layer thickness, and microstructured fuel distribution enhance efficiency and lifespan, achieving more than 3000 hours of continuous field use in portable DMFC systems [270,274].

Emerging technologies such as solid-state DMFCs offer improved energy densities and design flexibility. Sun et al. (2023) demonstrate a flexible, all-solid-state DMFC system with a specific power density of 27.4 mW cm^{-2}, opening applications in wearable devices or compact mobile tools for emergency responders [275]. Such innovations reflect the direction of current research towards compact, self-contained units suitable for rapid response and portable power delivery. The methanol fuel source can be stored in sealed, replaceable cartridges, which simplifies refuelling and enhances safety in field environments. Combined with simple user interfaces, these features contribute to rapid field-readiness and low cognitive load for operators [273,274].

Table 37: Performance Metrics for Methanol-Based Energy Systems

Metric/Property	Value per Module
Power Output (W)	5–100 W depending on configuration and use case [270,271]
Transport/Logistics	Compact and modular; suitable for handheld or packable configurations [270,272]
Operational Robustness/Durability	Reported durability of 3000+ hours; performance in rugged field conditions requires validation [270,274]
Maintenance	Low-maintenance; passive air-breathing stacks require minimal component replacement [273,274]
Rapid, Intuitive and Safe Field Deployment	Cartridge-based fuelling and passive operation allow for plug-and-play deployment [270,273]
Training	Minimal training required; user interfaces are simplified for field conditions [273]
Modularity and Microgrid Use	Stackable modules allow integration into small-scale grids or hybrid systems [270,275]
Acoustic Performance	Virtually silent due to electrochemical process and no mechanical components [270]
Circular Economy Principles	Methanol from captured CO_2 and waste enables renewable are in R&D [272,273]
Safety	Methanol toxicity mitigated via sealed cartridges and passive safety features [273,275]

II. Current Technological Development Trends/Development Trends & Market Analysis

Research in methanol-based energy systems is rapidly evolving to meet the demand for decentralised, portable, and resilient power sources. Key development trends include miniaturization, passive operation, enhanced catalyst performance, and integration into hybrid systems. These align closely with use cases in emergency response, humanitarian aid, and field-based operations.

Semi-active and passive DMFCs that reduce or eliminate the need for peripheral components (e.g., fans or pumps) have demonstrated superior reliability and efficiency under real-world conditions. Such systems can sustain long-duration missions without significant intervention, reducing operational complexity [270,273]. Research continues to refine fuel cell stack design, particularly in reducing catalyst layer thickness while maintaining power output, thereby lowering costs and improving manufacturability [271,274].

Another significant trend is the development of flexible DMFC architectures. For example, flexible solid-state DMFCs show promise for integration into textiles or foldable kits, which may power small communication or monitoring devices in disaster zones [275]. This innovation addresses the growing demand for wearable and ultra-portable power supplies.

Alias et al. (2020) highlight the importance of microstructured components in improving fuel utilization efficiency. These refinements are contributing to the viability of lightweight DMFC systems for intermittent loads, such as environmental sensors or satellite uplinks in remote areas [274].

From a market perspective, methanol's advantages as a liquid fuel, high energy density, low cost, and ease of transport, make it a promising candidate for deployment in remote and logistically challenging scenarios (for product examples and providers see Table 38 & 39). The methanol supply infrastructure, while still emerging, benefits from its compatibility with existing liquid fuel logistics chains [272,273].

Though widespread commercial deployment is still emerging, early-stage niche markets are forming, particularly in defence, disaster relief, and telecommunications. Product prototypes and pilot programs have demonstrated the viability of DMFCs in off-grid conditions, creating pathways for scaled production and broader adoption [270,273,275] (see Annex 1).

Table 38: Global market key providers for Methanol-Based Energy Systems [276]

Company	Headquarters (Country)
SFC Energy	Germany
Oorja Fuel Cells	USA
Blue World Technologies	Denmark
SerEnergy	Denmark
EFOY (by SFC Energy)	Germany
Horizon Fuel Cell	Singapore

Table 39: Examples for related products

Product	Seller	Link
EFOY Pro 2400	SFC Energy	Link
SereneU-5 G4	SerEnergy	Link
Oorja DMFC APU	Oorja Fuel Cells	Link
Blue Methanol Fuel Cell System	Blue World Technologies	Link
MODEL DMFC S1/S2	DMFC Corporation	Link
Siquens Ecoport 1500	Siquens	Link

III. Implications and Considerations for Emergency Response Organizations

Methanol-based systems offer unique advantages for emergency response operations where rapid deployment, silent operation, and autonomy are critical. Unlike combustion generators, DMFCs operate quietly and without harmful emissions, making them suitable for indoor use or in sensitive environments such as emergency shelters [270,273].

The liquid fuel format simplifies logistics; methanol cartridges are compact, stable, and easy to transport without pressurised tanks. These sealed cartridges mitigate toxic exposure risk and facilitate safe handling even by minimally trained personnel [272,273]. This characteristic enables personnel to maintain operations without deep technical training, ideal for high-turnover or volunteer-dependent missions.

The modularity of DMFCs supports integration with other power systems, such as solar or battery banks, enabling hybrid microgrid setups that improve resilience in unstable or energy-scarce regions [270,275]. As demonstrated in flexible DMFC systems, integration into portable diagnostic or telemetry equipment can extend capabilities in field clinics, mobile labs, or coordination hubs [275].

Field tests, including deployments exceeding 3000 continuous hours, affirm DMFCs' suitability for demanding conditions. Water-resistance, ambient temperature tolerance, and passive airflow mechanisms extend operability in harsh climates [270,274]. These performance traits ensure energy continuity during critical missions, disaster recovery, or remote monitoring campaigns.

Training requirements are comparatively low due to intuitive interfaces and simple maintenance, often limited to cartridge replacement and occasional filter checks [273]. These features reduce the burden on operators and make methanol systems highly deployable with little pre-deployment preparation.

In summary, DMFC-based systems may address several needs of emergency response units, subject to validation. As performance and integration technologies improve, methanol systems could play a role in decentralised emergency power, depending on demonstrated reliability and logistics.

3.2. Emerging highly promising technologies (EHPETs)

3.2.1. Wave Energy Converters

Status:	Market available / in Research and Development
Key words:	WECs, WEDs

Summary

Wave Energy Converters are mechanisms used in wave energy conversion technology, to capture, transmit and transform wave energy into electricity. There are several types of Wave Energy Devices, whose ongoing evaluation using different approaches, whilst carefully choosing their stationing is crucial to achieve optimal results. Wave power is being explored as a promising option, with market activity increasing in selected regions, though deployment remains constrained by harsh environmental conditions, limited infrastructure and high manufacturing costs. However, WECs currently offer limited direct potential for emergency response operations, since they are only suitable in cases where camps are going to be located near coastal areas where WECs' infrastructure is/ can be developed.

I. Technical Function and Description

A Wave Energy Converter (WEC) and a Wave Energy Device (WED) are almost synonymous. Generally, a WED is a physical structure which mainly receives the mechanical power from the oceanic wave and drives it in an exact direction. This promotes electrical generators to produce electricity. Whereas WEC generally means a converter used in wave energy conversion technology. Irregular mechanical energy captured from the wave is first converted into regular mechanical movement. The movement can be rotational or linear/translational. The rotational motion usually drives a turbine, which further drives a rotating electrical generator. Whereas the translational motion drives a linear electrical generator [277].
The wave energy devices and accordingly the wave energy convertors can be categorised in different types, using as a criterion the location, the take-off system and their working method. The location where a WED can be placed is either the shoreline (On-Shore), near the shore (Near-Shore), or offshore (Off-Shore). Different types off a WED's power take-off include hydraulic ram, elastomeric hose pump, pump-to-shore, hydroelectric turbine, air turbine and linear electrical generator. The WEDs can be classified based on their working method as either oscillating column (with air turbine), oscillating bodies (with hydroelectric motor, hydraulic turbine, linear electrical generator) and overtopping devices (with low-head hydraulic turbine). Subsequently the basic WEC types are: 1) point absorber buoys, 2) surface attenuators, 3) oscillating wave surge converters 4) oscillating water columns, 5) overtopping devices, 6) submerged pressure differentials, 7) floating in-air converters, and 8) submerged wave energy converters, with the underlined being the most common [277,278] Significant Performance Metrics of WECs are shown in Table 40.
Furthermore, considering the actual needs of wave power generation and the complexity of the working environment involved, three quantitative and 2 qualitative indicators can be selected to evaluate effectiveness of different WEDs. These are: 1) energy capture, 2) technology cost, 3) environmental friendliness, 4) reliability and 5) adaptability. [7] In addition, there are other approaches to evaluate not only a WEC's but also a site's competence. This is quite important since the correlation between geographical

characteristics and the implemented technology is quite strong and there is a significant interaction between them that affects energy production [279,280].

Table 40: Performance Metrics for Wave Energy Converters

Metric/Property	Value per Module
Power Output (W)	**High:** Typically, the power production of a WED ranges from 45KW to 750 KW. Optimal-sized and scaled WEDs can produce significantly more power, reaching up to 6 MW [278]
Transport/Logistics	**Demanding:** Tugboats, Barges, Dynamically Positioned Ships are used to transfer WEDs [278]
Operational Robustness/ Durability	**Low:** Typically, durability of a WED is characterised as low to medium. The WEDs are quite susceptible in harsh environments like the oceans [281]
Maintenance	**High:** Typically, the maintenance (preventive and corrective) of a WED is characterised as high to medium [279]
Rapid, Intuitive and Safe Field Deployment	**Low:** Typically, the positioning of a WED is quite demanding equally in scheduling, preparation, time and cost, thus its development hurdles are characterised as high to medium [281]
Training	**Demanding:** Operating WEDs require specialised knowledge in engineering as well as practical/ field experience
Modularity and Microgrid use	**High:** The modularity of WEDs is characterised as quite high since large facilities (farms) can be formed by combining several WEDs, that can lead to microgrid integration
Acoustic Performance	**Challenging:** The Marine life can be affected in terms of noise pollution by the WEDs' operation, since the noise production (transient or continuous) because of a WED can reach 140 db The coastal areas are also affected in terms of noise disturbance by the WEDs' placement and operation [280,282]
Circular Economy Principles	**Low:** Circularity is currently low and would need to be improved by incorporating recycled materials and maximising their lifespan. This can be quite challenging because the ocean's harsh environment is quite corrosive on WEDs' parts
Safety	**Medium:** Typically, the safety level of a WED is characterised as medium [279]

II. Current Technological Development Trends/Development Trends & Market Analysis

A dynamic estimation of the wave energy potential requires the evaluation of the capability of both the geographic area in producing it as well as the factors involved in exploring it (for product examples and providers see Table 41 & 42).
"Wave energy is a relatively underexplored renewable power generation technology" [283]. However, Wave Energy Converter technology is advancing and is expected to grow, with focus on increasing the WECs' energy capture-production, improving their Power Take-off systems and enhancing the WEDs' reliability and survivability while maximising grid integration and minimising operating costs and environmental impact. To this end, new WEDs' designs are being produced using improved Hydrodynamic systems materials and mechanisms with control systems that will utilise artificial intelligence (AI) technology, to forecast the wave energy, optimise harvesting performance and manage power generation systems [284–286].
Generally, By the year 2030 the oscillating water column sector is expected to grow at the fastest rate. The oscillating body converters technology is expected to continue to hold the largest share of the wave energy market, due to the high efficiency and ease of installation of the WECs using this technology in near-shore locations. The offshore sector is also expected to grow at the fastest rate, as offshore WECs can harness the most amount of wave energy, as wave energy resources are strongest in offshore locations [283].
A report by Ocean Energy Systems, a program of the International Energy Agency, states that there is a way for wave energy to generate 300GW by 2050 (which could power about 225 million homes, as reported by Cosmos). As pointed out by the World

Economic Forum, hitting this target would require wave energy efforts to increase by 33% per year [287].
In the field of wave energy converters, the number of scientific publications is approximately equal to the number of active patents. As publication activity continues to grow, this suggests that theoretical research is progressing in parallel with technological development.
China is the leading country in terms of patent filings, while Germany is currently not represented in the patent landscape. Within Europe, patent activity is limited to countries with extensive coastlines. Despite this regional concentration, overall research output in the field continues to increase (see Annex 1).

Table 41: Global market key providers for Wave Energy Converters

Company	Headquarters (Country)
Ocean Power Technologies	US
Eco Wave Power	Israel
CorPower Ocean	Sweden
Wello Oy	Finland
Calwave	US

Table 42: Examples for related products

Product	Seller	Link
PowerBuoy®	OceanPowerTechnologies	Link
HiWave-5	CorPower Ocean	Link
Our xWave	Calwave	Link
CETO® Technology	Carnegie Clean Energie	Link
AMOG Wave Energy Converter – Gen 1	AMOG Holdings Pty. Ltd	Link
OE 12 Buoy	OceanEnergy	Link
OE 35 Buoy	OceanEnergy	Link

III. Implications and Considerations for Emergency Response Organizations

The placement of Wave Energy Convertors, together over a selected area, forming a farm or a park, requires quite a lot of planning and logistics. The logistics involved include first moving the parts needed to construct the facilities and then transmitting the power, which requires additional infrastructure such as onshore substations, underground cables and transmission lines to connect to the grid. The installation of a wave energy farm is fixed and used in the specific area where it is placed. Thus, only power plants and cities located near them could benefit directly, since it is very difficult to transmit ocean wave produced electricity to long distances. Subsequently WECs could probably only facilitate emergency response organisations, with providing power, if rescue camps were set up next to them.
There are several considerations when it comes to harnessing wave energy. First, wave power is an emerging energy technology that is costly and still in the early stages of development. The initial installation of WEDs requires a significant capital investment to develop systems that can withstand the harsh marine environment. Moreover, ongoing maintenance is costly and requires specialised equipment and skilled personnel. Wave power is also highly dependent on wave characteristics and water density. In some areas, wave behaviour is unreliable, and it becomes difficult to accurately predict wave power whereas the performance of WECs is significantly reduced in rough weather. As a result, there are no energy companies using wave energy on a large scale, which would reduce costs. Additionally, *'a through-life safety approach that systematically identifies system hazards, assesses and evaluates risks at each stage'* is required when producing a WEC. The greatest risk of WECs is system failure, which results in their inability to operate and the potential release of toxic chemicals into the ocean. There is also the possibility of a human accident when approaching them or even a sabotage. One other main concern is the impact on marine life. The presence of wave energy devices can disrupt sea habitats and behaviour in several ways, including disturbing thalassic mammals and altering the migration patterns and behaviour of marine species. Another consideration is the location of the WECs, since the wave energy

harvesting power stations need to be close to the coast and near cities and other populated areas to perform and power them directly. However, these areas are major thoroughfares for cargo ships, cruise ships, recreational vehicles and beachgoers. The installation of a wave energy harvesting device will disrupt all these parties since, besides being a physical obstacle, it may also alter seascape aesthetics and generate noise pollution [282,288–290].

3.2.2. Sodium-Ion Batteries

Status:	Market available / in Research and Development
Key words:	NIBs, SIBs, or Na-ion batteries

Summary

Sodium-ion batteries are a type of rechargeable batteries, which use sodium ions (Na+) for electrodes and the electrolyte conductor may be aqueous or non-aqueous. Sodium is abundant and geographically widespread, which can contribute to cost reductions and potentially lower environmental impacts compared to lithium. Their use is more efficient in stationary energy storage cases due to their low energy density and the consequent large volume required. This shortcoming is addressed by research & development of start-ups and large battery manufacturers. Their comparatively lower risk of thermal runaway improves transport safety, which could increase suitability for certain emergency operations.

I. Technical Function and Description

Sodium-ion Batteries are a type of rechargeable batteries, which use sodium ions (Na^+) as their charge carriers instead of lithium ions (Li+) that employ the conventional lithium batteries. Sodium-ion batteries are composed of the following elements: a positive electrode or cathode based on a sodium-based material and a negative electrode or anode, typically made of hard carbons or intercalation compounds.
During the discharging of the battery, the sodium-ions move from the anode *(of preferred material the disordered carbon [291])* to the cathode *(of one of the three materials [291]: transition metal oxides, polyanionic compounds and Prussian blue analogues)* through a liquid electrolyte that separates the electrodes and functions as an electrical conductor. The latter contains dissociated sodium salts in polar protic or aprotic solvents [292] or can be made up of aqueous solution (such as Na_2SO_4 solution) [293]. The current is produced by this potential difference. When charging, the sodium ions return to the anode until a predetermined end-of-charge voltage is reached. When the battery is discharged, sodium ions move from the anode to the cathode through an electrolyte - a substance composed of free ions that functions as an electrical conductor - resulting in the potential difference that produces the current. When the battery is charged, the sodium ions return to the anode until a predetermined end-of-charge voltage is reached (see Table 43).
Compared to lithium-ion batteries, sodium-ion batteries offer potential advantages (e.g., cost, safety), while drawbacks such as lower energy density and efficiency currently necessitate larger system sizes.

Table 43: Performance Metrics for Sodium-ion Batteries

Metric/Property	Value per Module
Energy density	100-170Wh/kg, R&D to reach 190Wh/kg [294]
Power output	Up to 1000W/kg
Average voltage	0-4.3V / 800-1400 V
Transport/Logistics	Usually in larger volumes (due to relatively low energy density) Can be EU pallet compatible Obtained UN numbers[1] and included in the regulations for transportation of dangerous goods, it is expected that less stringent regulations to be applied.
Operational Robustness/ Durability	Performance and excellent capacity at -20 °C - +60°C Lifetime is 2000-6000 cycles to 80% of capacity. R&D to reach 8000-10000 cycles [295]
Maintenance	Storage temperature -30 °C - +60°C Of low-maintenance due to their inherent stability and robust design
Rapid, Intuitive and Safe Field Deployment	An example of the cycling rates is a range of 2C (0.5 hour) to C/10 (10 hours. Also, inherently capable of fast charging (sub-20 min charge)
Training	
Modularity and Microgrid use	Sodium-ion batteries can be designed in various sizes and configurations, allowing for small-scale and larger-scale applications Individual battery modules can be combined to create larger battery banks,
Acoustic Performance	Low, normal operating sound is some level of electrochemical noise
Circular Economy Principles	Material in use, easy to recover and reuse through battery recycling and obtained with environmentally friendly and non-destructive techniques
Safety	Thanks to their relatively low risk of thermal runaway, they are considered non-flammable. pose smaller safety risks for transportation, compared to traditional lithium-ion batteries. Claimed to be safely transported at 0% state of charge, while lithium-ion require 30% of charging. Meets the national standard GB/T31485-2015 [296]

II. Current Technological Development Trends/Development Trends & Market Analysis

Research on Sodium-ion batteries was launched at the end of 2000 decade, as an alternative to Lithium-ion batteries, for which lithium supply was expected to be reduced along the years with consequent significant price increase (for product examples and providers see Table 44 & 45).

In 2010 the Na-ion technology was identified as priority for the energy storage sector by both the European Commission and the Department of Energy of the USA [296] Its primary use was identified for the grid electricity storage applications, while main research objective was to achieve a "lower cost of stored energy (LCOSE)" over the lifetime of the system <$0.1/kWh [297]. Research was launched globally for non-lithium-ion batteries.

Already in 2011 Aquion Energy, a spinoff of the Carnegie Mellon University, launched its first product, a battery stack of 1.5kWh storage with many charge/discharges cycles, relatively low cost and low overheat risk. After the provision of the market for some commercial applications, in March 2017 went bankrupt due to inability of getting more funding. On the other hand, Faradion Ltd, also founded in 2011, actively working since then to establish Na-ion technology in energy storage, has achieved 21 patent families and has been recently acquired by Reliance Industries Ltd., India's largest private company with the intention to heavily invest in Sodium-ion battery technology as a sustainable, low-cost, safe and efficient alternative to lithium-ion and lead technology batteries.

In Europe, French Tiamat is considered a leading manufacturer in this field, together with AMTE Power PLC a UK-based developer and manufacturer of lithium-ion and sodium-ion battery cells for niche markets, and the Swedish Altris. Tiamat aims to build a gigafactory entirely dedicated to the production of sodium-ion battery cells, with EU and French-state funds.

In USA, Natron is the only commercial sodium-ion battery manufacturer in the USA, currently building a sodium-ion battery gigafactory in North Carolina, aiming to be a key player in the US energy storage market.
Nevertheless, the Asia Pacific region, particularly China, dominates the sodium-ion battery market. This dominance is driven by large-scale manufacturing capabilities, significant investments in research and development, and supportive government policies promoting renewable energy and electric vehicle adoption. Key players like HiNa Battery Technology Co. Ltd (producing mainly Energy Storage Systems) and the Chinese power battery giant CATL (which marked innovation in the industry with the production of a battery of energy density as high as 160Wh/kg) are leading the way this region, while Chinese automotive company BYD started recently the construction of a sodium-ion battery facility in China mainly aiming to incorporate these batteries into electric vehicles. The facility is part of BYD plans to diversify its energy storage solutions with more cost effective and environmentally sustainable options.
To conclude, the Sodium Ion Battery Market was valued at 1.29 USD Billion in 2023 and is projected to grow to 8 USD Billion by 2035. The market is driven by the demand for sustainable energy storage solutions and the depletion of lithium resources, leading to increased interest in sodium-ion technology [298].
Research and Development activities focusing on enhancing the performance of sodium-ion batteries, including increasing energy density and cycle life, have gained momentum over the recent years. Big players, such as Tesla and Panasonic are exploring sodium-based technologies and are leading investments in the area, what enhances both product development and viability, but also production capacities as well [299]. This technology aligns with governmental priorities for clean energy and sustainable alternatives.
Sodium-ion batteries represent a developing technology that continues to attract considerable research interest. Although the number of annual publications remains high, the growth rate has recently begun to decline, possibly as a result of the already extensive body of literature.
The patent landscape is dominated by Chinese applicants, with no European company represented among the top 100 patent holders in this field (see Annex 1).

Table 44: Global market key providers for Sodium-Ion Batteries

Company	Headquarters (Country)
AMTE power, acquired by LionVolt	UK / Netherlands
Faradion Ltd acquired by Reliance Industries	UK / India
Altris	Sweden
Natron Energy	USA
Tiamat	France
HiNa Battery	China
CATL	China

Table 45: Examples for related products

Product	Seller	Link
BluePack™ Critical Power Battery	Natron Energy	Link
NACR/NaCP products	HiNa Battery	Link
Sodium-ion high power battery	Tiamat	Link
Altris NaBOB patented electrolyte	Altris	Link
MC Cube-SIB ESS	BYD	Link

III. Implications and Considerations for Emergency Response Organizations

Sodium-ion batteries are considered to have unique advantages such as high energy conversion efficiency, long cycle life, good stability, low maintenance cost, and good safety.

Sodium-ion batteries could be used in camps deployed during emergencies as a stationary energy storage solution. Batteries can store energy generated by renewable energy power generation systems for its use during the time that generation is unavailable, providing a stable and safe solution. Being safer than lithium-ion batteries for transportation, it is expected that they can soon travel with less restrictions (they obtained UN numbers[13] only in 2024), what makes their transportation more flexible and less costly. On the other hand, due to their rather low energy density, they need to be quite bulky to be efficient. For this reason, they are considered more suitable for longer-term Emergency Shelter installations, rather than for Bases of Operations or short-term shelters that require rapid deployment and dismantling by first responder teams. Ongoing R&D is expected to deliver products with higher energy density, which may broaden their use in faster-deployment settings in the future.

They also have a wide range of operational and storage temperature, what allows its use and warehouse storage by multiple organizations and in different circumstances with no particular restrictions. They demonstrate comparatively strong performance in low temperatures, compared to other types of batteries, as they are reported to retain over 92% capacity even in freezing conditions of -20°C [299].

Thanks to their fast-charging capabilities and high energy storage potential, they can be also used for charging of electric vehicles of emergency response organizations when recharging stations connected to the grid are not available within a reasonable distance.

[13] UN number (United Nations number) is a four-digit number that identifies hazardous materials, and articles (such as explosives, flammable liquids, oxidizers, toxic liquids, etc.) and is assigned by the United Nations Committee of Experts on the Transport of Dangerous Goods.

3.2.3. Metal Hydrides of Hydrogen Storage

Status:	Research and Development
Key words:	H_2, MeH, Metal Hydride, Energy Storage, Hydrogen Storage

Summary

Metal Hydrides are one of several investigated hydrogen storage approaches utilising the chemical bonding of hydrogen gas with metals and metalloids to create a stable storage medium, which can release Hydrogen when required. This technology aspires to solve a key problem in Hydrogen as an energy coin, the problem of effective and efficient storage. As a stable and more secure medium of storage than conventional cryogenic or pressurised gas storage, metal hydrides represent a potential approach, providing a solid and stable reversible hydrogen reservoir. For broader adoption, several technical and economic challenges remain, such as weight per volume of storage, cost of materials, heat management and eventually, actual amount of storage medium required to store sufficient Hydrogen to fuel efficient energy production.

I. Technical Function and Description

To substitute large gas tanks or cylinders, metal hydrides utilise the chemisorption of hydrogen gas onto metal substrates under specific temperature and pressure conditions to create chemically stable meshes, which can reversibly re-release the absorbed hydrogen when required. Metal Hydride storage uses an array of metal meshes in several configurations, such as cylinders or blocks, which are porous and allow for hydrogen to chemically bind onto a metal substrate, creating a compound with Metal and Hydrogen ions bound together.

The key behind metal hydrides as a hydrogen source, hence an energy source, is this reversible hydrogen absorption process using heat and pressure as the regulating factors (see Table 46). Hydrogen is a small molecule that can be absorbed in the metal configuration and then chemically bind to it. This process yields a stable product in proper conditions, releasing heat. When that heat is introduced back into the system (raising the temperature), Hydrogen is released from the metal mesh and back into the circulation.

The following table includes some basic information on the use of Metal Hydride tanks as a storage medium for Hydrogen [121,300].

Table 46: Performance Metrics for Metal Hydride Storage

Metric/Property	Value per Module
Energy Density (indicative values converted from Hydrogen weight stored)	**Gravimetric Hydrogen Storage Capacity (wt%):** 1% to 9% (or 0.01-0.09 kg H_2/kg hydride) **Volumetric Energy Density (kWh/L):** 1.22 kWh/L (for TiMn2 metal hydride tank) **Gravimetric Energy Density (kWh/kg):** 0.31 kWh/kg (for TiMn2 metal hydride tank) [301]
Transport/Logistics	*Heavy tanks, mostly suitable for stationary applications (energy storage areas in facilities)*
Operational Robustness/ Durability	Metal Tanks are generally resilient, main concern is embrittlement after multiple charge/discharge cycles
Maintenance	Tank replacement when performance drops due to embrittlement, temperature/pressure monitoring. Dry conditions ideal and hydrogen stream must be free of moisture
Rapid, Intuitive and Safe Field Deployment	Large vehicles may have metal hydride storage but in general this is a stationary deployment (facility or larger scale storage)
Training	. / .
Modularity and Microgrid use	Multiple tanks can be linked to create storage stacks
Acoustic Performance	. / .
Circular Economy Principles	Metals from tanks can be recycled after embrittlement, no other waste produced, only circulating substance is Hydrogen
Safety	Safe, temperatures and pressures regulated (120 °C and 200 °C, close to atmospheric pressures)

II. Current Technological Development Trends/Development Trends & Market Analysis

Conventional pressurised or cryogenic storage of pure H_2 is the current preferred method for mobile on-board storage of Hydrogen, as well as the main storage for larger scale or stationary applications (for product examples and providers see Table 47 & 48). Li-MH batteries are electricity storage devices but not hydrogen storage, essentially being market-ready indirect competitors. In general, hydrogen storage is currently a tight bottleneck in widespread adoption of Hydrogen as an energy source, no matter the approach to storage. Factors such as the weight of the Metal Hydride tanks, hydrogen embrittlement and the high Hydrogen purity, coupled with low humidity, are the inhibiting factors preventing Hydrogen from reaching a more widespread use.
Regarding the relevant market data, the increasing demands from the ammonia and methanol industries, along with the slow increase in hydrogen use as an energy source, means that hydrogen storage is a growing market, starting from an estimated USD 1.45 billion in 2023, is poised for substantial growth, expected to hit USD 8.06 billion by 2032, presenting a compound annual growth rate of 21%. However, a very low percentage of this belongs to metal hydride storage, yielding the majority to conventional pressurised or cryogenic Hydrogen instead. An increase in the need for Hydrogen, or a transition to hydrogen as mobility fuel could accelerate market growth, intensifying the research for Hydrogen storage [302].
Table 2 below shows some main providers of Metal Hydride storage and Table 3 examples of some available products in the market. Most of the products can be customised according to the needs.
The technology is predominantly situated within the research domain, although a limited number of patents have already been filed. As with crystalline silicon photovoltaic cells, France is a key actor, particularly through the Commissariat à l'énergie atomique et aux énergies alternatives. Apart from this, patent activity is primarily concentrated in China. In Germany, BASF SE ranks 20th, holding five active patents.
Research output in this field has remained relatively stagnant since the 2010s (see Annex 1).

Table 47: Global market key providers for Metal Hydride Storage

Company	Headquarters (Country)
Mincatec	France
HYDROGENERA	Bulgaria
Bronkhorst	Taiwan
MAHYTEC	France
GRZ Technologies	Switzerland
MetHydOr	Italy
h2planet	Italy
Harnyss	USA

Table 48: Examples for related products

Product	Seller	Link
MYH2	H2planet	Link
Hydor system (modular/rack)	MetHydor	Link
Metal Hydrid containers	Hydrogenera	Link
Dash M-series	GRZ technologies	Link

III. Implications and Considerations for Emergency Response Organizations

There are several challenges for Metal Hydride storage on its road to the market, which directly relate to the applications envisioned by emergency response organizations. To begin with, metal hydride storage has a relatively high energy density by volume, but a relatively low energy density by weight (kWh/kg), ranging from 1% to 9%. As such, storage tanks end up being much heavier than other systems for on board storage, with tanks weighing more than 250kg. This limits the use of metal hydrides for mobile applications at present. This currently restricts portable applications for emergency response organizations, and the stationary storage deployments need to be secured on solid ground. Interestingly, for applications that already use ballast, like forklifts or cranes, such systems can use the added weight as benefit, providing fuel storage while also acting as counterbalances if necessary [303].
Raw material and manufacturing costs remain comparatively high, currently limiting competitiveness with conventional storage tanks; particularly the intermittent alloys and alloy metals for hydrides are currently costly and cannot compete with an empty storage tank for hydrogen, no matter it's shell complexity or building materials. Concerning safety, metal hydrides tend to react violently with moisture in the air so the process needs to remain dry and hydrogen fed during recharging needs to be rid of humidity [304]. Thus, increased cost and potentially precarious conditions may deter emergency response organizations who may look for a more rugged or cost-effective method of storage from opting for Metal Hydride storage.
Another fundamental issue with the chemical storage of hydrogen in metals is Hydrogen embrittlement. The repeat adsorption and desorption (the interaction of hydrogen with the metal mesh) causes the structure to become brittle, change its mechanical properties and develop cracks that may lead to complications. This situation is worsened depending on the conditions, the presence of water or contaminants and the life-cycle of the tank, and can so far be mitigated by condition controlling, special coatings or additives and clean reagents that aspire to minimise the effect [305]. Hydrogen embrittlement is an issue in Hydrogen circulation in general, and concerning storage in particular, it raises concerns for response forces regarding long-term reliability and lifecycle costs. The decreasing performance due to embrittlement coupled with the increased costs to eventually replace the degrading tanks may pose as a deterrent for adoption of this storage approach, or hydrogen solutions in general.

3.2.4. Solid-State Batteries

Status:	In research & development; limited early-stage commercial applications
Key words:	solid electrolyte, next-generation battery

Summary

Solid-State Batteries are innovative energy storage solutions that replace traditional liquid electrolytes with solid electrolytes, significantly enhancing safety, energy density, and longevity. Primarily targeted for applications in electric vehicles, aerospace, and grid storage, these batteries may reduce emissions in emergency response operations by offering safer, higher-capacity energy storage. Although not yet widely available and currently associated with higher costs compared to lithium-ion systems, due to limited large-scale production capabilities. Ongoing R&D efforts are projected to improve market presence and cost-competitiveness in the 2025–2035 timeframe.

I. Technical Function and Description

Solid-State Batteries (SSBs) are advanced energy storage systems that replace the traditional liquid electrolytes found in lithium-ion batteries (LIBs) with solid materials. This change significantly improves safety, energy density, and longevity (see Table 49). SSBs are under active development for electric vehicles (EVs), aerospace, and stationary energy storage due to their enhanced performance characteristics [306,307].

Unlike LIBs, which use liquid or gel-like electrolytes, SSBs utilise solid electrolytes made from ceramics, sulphides, or polymers. This substitution eliminates flammable components, reduces the risk of thermal runaway, and allows for the use of lithium metal anodes. Lithium metal offers much higher theoretical energy density and improved cycling life due to reduced side reactions at the electrode–electrolyte interface [306,308].

Structurally, SSBs maintain the three core battery components: anode, cathode, and electrolyte. However, the liquid electrolyte and separator in LIBs are replaced by a solid electrolyte, which often serves both functions—conducting lithium ions and preventing short circuits. This design enables closer electrode integration, helps suppress dendrite formation, and supports thinner, more compact battery configurations (Burton et al., 2025). These properties indicate potential suitability for critical applications, including emergency response and operation under extreme environmental conditions [309].

There are several types of solid electrolytes, each with distinct properties and limitations:

- **Solid Polymer Electrolytes (SPEs):** Lightweight and flexible, often compatible with lithium metal anodes. However, they suffer from low ionic conductivity at room temperature and typically require elevated temperatures [310].
- **Garnet-Type Electrolytes (e.g., LLZO):** Highly stable with lithium and thermally robust but are brittle and difficult to process. High interfacial resistance remains a challenge [310].

- **NASICON-Type Electrolytes:** Offer good thermal and electrochemical stability, though compatibility with lithium metal can be limited in some compositions [310].
- **Sulfide-Based Electrolytes (e.g., Thio-LISICON):** Deliver very high ionic conductivity (up to 10^{-2} S/cm) and are easily processable. However, they are highly reactive to moisture, producing toxic hydrogen sulfide gas (H_2S) [310].

Despite their advantages, SSBs still face considerable hurdles regarding large-scale manufacturing, cost efficiency, and interface engineering [307,311]. Nevertheless, technological progress is expected to accelerate their market adoption and economic viability significantly between 2025 and 2035 [306,312].

Table 49: Performance Metrics for Solid State Batteries

Metric/Property	Value
Energy Density	State-of-the-art solid-state batteries (SSBs) show gravimetric energy densities of 300–500 Wh/kg and volumetric densities up to 1150 Wh/L, depending on the solid electrolyte and cell architecture [311].
Transport/Logistics	Solid-state batteries (SSBs) offer reduced weight and size at the pack level compared to conventional lithium-ion batteries, due to higher energy density enabling smaller, lighter battery systems [313,314]. However, transport and packaging requirements remain similar to lithium-ion batteries, as they are regulated under the same hazardous materials rules (e.g. UN 3090/UN 3480) and must be shipped at ≤ 30 % state of charge according to IATA/ICAO guidelines [315].
Operational Robustness/ Durability	Solid-state batteries (SSBs) have demonstrated cycle stability of over 1,000 charge/discharge cycles with ≥ 90–95% capacity retention under controlled conditions, as seen in prototypes from Toyota and others[316]. However, durability is strongly influenced by mechanical degradation mechanisms, including interface fractures, void formation, and electrode stack pressure, that can impair long-term performance if not properly engineered [317].
Maintenance	Solid-state batteries require very low maintenance, as their solid electrolytes eliminate liquid electrolyte degradation and leakage issues, removing the need for periodic electrolyte inspections. Battery management systems still perform typical monitoring, but the overall maintenance demands are substantially lower compared to conventional liquid-electrolyte systems [318].
Rapid, Intuitive, and Safe Field Deployment	Recent deployments of SSB and semi-SSB systems (e.g., WeLion and Ion Storage Systems) show that these batteries can be safely integrated into existing infrastructure and used in real-world grid or defense settings [319–321].
Training	No specific data on training duration are available.
Modularity and Microgrid use	Recent advances show solid-state batteries can be implemented in modular, scalable formats for microgrid deployment, enabling system-level fault isolation and control, while pilot projects confirm use in multi-module grid-connected systems of up to several hundred MWh [319,322].
Acoustic Performance	No specific data on acoustic performance are available.
Circular Economy Principles	Solid-state batteries require chemistry-specific recycling strategies, including dissolution-based and direct regeneration techniques, to recover both electrolyte and electrode materials. The adoption of flexible, modular recycling infrastructures is seen as essential to support circular economy principles and maximise resource recovery [323,324].
Safety	Modern solid-state lithium batteries (SSLMBs) improve safety by using non-flammable solid electrolytes, significantly reducing fire risk compared to liquid-electrolyte systems. Nonetheless, they remain vulnerable to thermal runaway, interfacial chemical instability, and lithium dendrite formation, potentially causing exothermic reactions or internal short circuits [325].

II. Current Technological Development Trends/Development Trends & Market Analysis

As of early 2025, fully solid-state batteries are not yet commercially available (for stakeholders see Table 50). However, several manufacturers are actively developing and testing this technology, with plans to introduce it in the near future. Forecasts indicated that with the introduction of oxide and sulphide electrolyte technologies, pilot production could begin as early as 2025, with overall capacity expected to grow to between 15 and 40 GWh by 2030, and up to 120 GWh by 2035 [326]. Pricing remains a significant challenge; acquisition costs for SSBs are currently estimated at 2–3 times higher per kWh compared to conventional, primarily due to the limited scale of production and immature supply chains. However, Forecasts predict a price drop to approx. 70–80 % of the original costs in 2030 [326]. Research activities mainly focus on electric vehicles and are concentrated in Asia, with major roles played by companies and institutions in Japan, South Korea, and China, while emerging efforts in the United States are also notable. These factors underline the current fragmentation of the SSB supply chain and the critical need for further scaling to achieve cost competitiveness [326].

In Europe, robust research and development efforts are underway to advance SSB technology, particularly in innovative materials and cell design, yet industrial-scale production lags behind that of Asian and U.S. competitors. European initiatives, such as those supported by the national research funding and coordinated through projects like the Battery Research Factory.

Although some products on the market, like Yoshino, market their portable batteries as "solid-state," they actually contain a solid-state electrolyte alongside a liquid component, making them more accurately classified as semi-solid or hybrid solutions. Despite ongoing debate over terminology, semi-solid or hybrid solutions demonstrate improved safety and longevity compared to traditional lithium-ion batteries [327].

Since 2015, the number of scientific publications on solid-state batteries has increased significantly, reaching over 2,000 publications in 2024. The patent landscape in this field is primarily led by Japan, with Toyota as the most prominent applicant, followed by South Korea, particularly through companies such as LG and Samsung. By contrast, Chinese entities are only minimally represented.

Within the European context, Germany leads patent activity, with key contributions from Robert Bosch GmbH, BMW AG, and the Volkswagen Group (see Annex 1).

Table 50: Overview of relevant Stakeholders for SSB development

Organisation Name	Headquarters Location	Technology Focus
QuantumScape	USA, California	Developing lithium-metal SSBs for electric vehicles with Volkswagen partnership.
Solid Power	USA, Colorado)	Producing sulfide-based SSBs, with backing from BMW and Ford.
ProLogium Technology	Taiwan (Taipei)	Developing ceramic-based SSBs for EVs and energy storage.
Toyota	Japan	Focused on oxide-based SSBs for hybrid and fully electric vehicles.
Sakuu	USA California	Pioneering 3D-printed SSBs
Factorial Energy	USA	Developing SSBs with increased energy density, partnering with Mercedes-Benz and Stellantis
Samsung SDI	South Korea	Researching high-performance SSBs for consumer electronics and EVs
BASQUEVOLT	Spain	Developing next-generation lithium SSBs for mobility and stationary applications.
CIC energiGUNE	Spain	Research in solid-state electrolyte chemistry and thermal energy storage.
Fraunhofer ISI	Germany	Evaluating SSB development potential.
Ilika	UK	Developing thin-film SSBs for IoT, medical, and industrial applications
Blue Solutions (Bolloré Group)	France	Producing polymer-based SSBs for buses and stationary storage.

III. Implications and Considerations for Emergency Response Organizations

Solid-state batteries (SSBs) offer significant advantages for emergency response organizations by enhancing the safety, logistics, and reliability of energy supply in crisis scenarios. Their design, which replaces flammable liquid electrolytes with solid-state materials, greatly reduces the risk of fire or explosion during transport and use. This safer chemistry simplifies regulatory requirements for shipping and enables secure deployment by truck, rail, or even air [318].

Owing to their high energy density and compact form factor, SSBs reduce both volume and weight in logistical chains, making them suitable for mobile units, containerised power systems, and temporary shelters. Their modularity further allows for scalable configurations, ranging from individual storage units to fully integrated microgrids, facilitating tailored energy solutions based on situational needs [318].

In terms of operational performance, SSBs excel under harsh environmental conditions, including extreme heat, cold, and humidity. Unlike conventional lithium-ion batteries, they maintain stability and performance without the risk of thermal runaway, even in disaster-prone or moisture-heavy environments. This makes them particularly valuable for deployment in coastal areas, flood zones, or locations with extreme temperatures [309,310].

Training requirements for SSB systems are expected to be moderate. While less maintenance is needed due to the absence of liquid electrolytes, personnel must still be trained in battery management, integration into microgrid controllers, and basic troubleshooting to ensure safe and effective use in the field [311].

Although SSBs offer safety advantages, risks remain under conditions such as mechanical damage or improper system integration. To mitigate these, robust casings, tamper-proof enclosures, and automated battery management systems (BMS) are recommended. These systems monitor thermal loads, voltage, and state-of-health parameters in real time, enhancing the resilience and safety of battery deployment in critical environments [306,312].

3.3. Emerging moderately promising technologies (EMHPETs)

The emerging, moderately promising technologies can be divided into two categories: established topics with several thousand publications and patents, and emerging topics with fewer than a thousand publications and patents (see Annex 1).

Established technologies include **perovskite and tandem solar cells**, which continue to be intensively researched. In this area, China is the sole player on the patent side. Another example is **lithium-sulfur batteries**, which exhibit very strong research activity with over 14,000 publications (with a rising trend). The patents, currently at 3,000, are also on the rise, with China and the USA leading in this field. In Europe, Germany, particularly through *Robert Bosch GmbH*, holds a leading position. **Metal-air batteries** have also experienced a nearly linear increase in research since 2010 and continue to be intensively studied. However, European patents are scarcely represented in this area; the leading players are South Korea, China, and the USA, with Israel also being an interesting player in this context.

In contrast, the less established technologies are still in the development phase. This includes **solid-state wind energy technologies**, where China takes the lead, while Spain is the only European country able to keep pace. Research in this area is slowly gaining momentum. The **airborne wind & kites technology** is strongly represented in Europe, particularly in Denmark, but has a very low number of patents (under 100) and publications, with a declining trend.

On the other hand, research **in hydrogen-fueled internal combustion engines (H2 ICEs)** is currently increasing significantly, and patents are expected to follow soon. Europe is leading in this area, especially Germany (*Robert Bosch GmbH*), Sweden (*AB Volvo*), the United Kingdom (*Infineum INT Ltd*.), and Belgium (*Umicore NV*). Methanol is at a similar stage of development, with the USA, represented by companies like *Caterpillar Inc*. and *Chevron USA Inc*., being more in focus. In Europe, Germany, particularly through *Robert Bosch GmbH* and *MAN Energy Solutions SE*, is also active.

3.3.1. Perovskite & Tandem Solar Cell

Perovskite and tandem PV cells are next-generation photovoltaic technologies with high power conversion efficiencies, reaching over 25% for perovskites and exceeding 33% for perovskite-silicon tandem configurations, by stacking two complementary absorbers to capture a broader solar spectrum [328]. Their lightweight, flexible design and expected lower-cost manufacturing make them promising alternatives to conventional silicon photovoltaics [328]. However, their commercialization faces challenges related to environmental stability, as perovskites are highly sensitive to moisture, heat, and UV exposure, leading to fast degradation over time [329,330]. Advances in encapsulation techniques and material engineering are being explored to enhance their durability and operational lifespan [329–331]. Tandem solar cells mitigate some of these issues by integrating silicon, improving overall efficiency and longevity [332].

Despite these challenges, perovskite and tandem solar cells offer strong potential for emergency response operations, particularly in field camps such as Boo & ES. Their high efficiency and rapid deployability make them ideal for powering essential services. Their lightweight, flexible design enables quick transport and installation in remote or disaster-affected areas. Furthermore, tandem configurations maximise energy output in space-limited environments. Perovskite-silicon tandem PV panels require significantly less space (ca. 40%) than traditional silicon PV panels to generate the same amount of energy Though not yet as mature improvements in stability and encapsulation are steadily enhancing their durability, making them increasingly relevant for off-grid and mobile energy needs in emergency scenarios in the near future. Relevant stakeholders for development are Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE), Oxford PV, LONGi, EPFL (École Polytechnique Fédérale de Lausanne, Switzerland), IMEC (Interuniversity Microelectronics Centre, Belgium), CEA-Liten (Commissariat à l'énergie atomique et aux énergies alternatives, France), Instituto de Energía Solar (IES, Spain).

3.3.2. Airborne Wind Energy Systems

Airborne Wind Energy Systems (AWES) harness wind power at high altitudes using tethered wings or aircraft, operating between 200 and 600 meters where wind speeds are stronger and more consistent than at ground level. AWES are classified into *Ground-Gen* systems, which convert the mechanical energy from the tether into electricity at a ground station, and *Fly-Gen* systems, where airborne turbines generate power and transfer it via conductive tethers [333].

One of AWES's main advantages is its ability to capture wind energy efficiently through crosswind flight, significantly increasing power output. Compared to conventional wind turbines, AWES requires fewer materials, making it cost-effective and environmentally friendly. Its flexible deployment, particularly offshore and in remote areas where traditional wind farms are impractical, adds to its appeal. Additionally, AWES can be optimised to function during lower wind speeds, increasing profitability in fluctuating electricity markets [333].

However, challenges persist, including tether durability under dynamic loads, autonomous flight control, and integration with energy markets. Airspace regulations and aviation safety concerns must also be addressed before widespread adoption. Companies such as KiteGen (Italy), Ampyx Power (Netherlands), SkySails Power (Germany), and TwingTec (Switzerland) are actively developing prototypes, yet large-scale commercialization remains in progress [333,334].

Recent research suggests a shift from cost-driven AWES design toward value-driven optimization. Instead of focusing solely on minimising the Levelised Cost of Energy (LCoE), studies highlight the importance of maximising revenue through energy market integration. The Levelised Profit of Energy (LPoE) metric, which accounts for fluctuating electricity prices, indicates that systems optimised for low-wind-speed operation can yield higher returns in deregulated energy markets. While such market-oriented approaches dominate current research, off-grid applications like those targeted in POWERBASE have not yet been a primary focus. This technology could become particularly promising once development moves toward automated, easy-to-use solutions, which would enable reliable power generation across a wide range of geographical settings—potentially offering a much broader application spectrum than micro-hydro systems [335].

With advancements in autonomous control, composite materials, and market-based system design, AWES could play a key role in the renewable energy transition, particularly in offshore wind energy expansion and grid stabilization through flexible power generation [334,335].

Zeppelin-carried high-altitude wind power systems are a sub-type of airborne wind energy, sharing the same principle as kite or drone systems: a tethered flying device captures strong, steady winds at altitude and transmits the power to the ground. Current projects remain at the pilot and early-demonstration stage, with a few prototypes tested but no large-scale commercial deployment to date.

3.3.3. Solid-State Wind Energy Technologies

Solid-State Wind Energy Technologies harness wind power without traditional rotating blades, instead utilising electrohydrodynamic processes [336], vortex-induced vibrations [337,337–339], or enclosed (or semi-enclosed) wind turbine systems [340]. Bladeless subtypes eliminate mechanical wear and significantly reduce maintenance needs. They don't require heavy foundations or complex installation. While conventional wind turbines achieve higher efficiency per unit due to their large swept area, solid-state designs trade some power output for a more compact, quieter, and low-maintenance alternative. Although their efficiency per unit is expected to be lower, requiring multiple units to match traditional turbines, they can be deployed in closer proximity without significant energy losses [337]. Most solid-state wind technologies are still in early development stages, typically ranging from TRL 3 prototypes to 6, though some designs, like Vortex Bladeless, are nearing commercial readiness. Notably, vortex-induced vibration systems are most effective in open, unobstructed areas where wind flows freely, while enclosed wind turbine systems with shrouds are especially advantageous for urban settings like rooftops, where space constraints and wind direction and speed variability are factors[341]. However enclosed wind turbines are not limited to this area.

For emergency operations and mobile energy supply in field camps, solid-state wind technologies could offer lightweight, modular, and low-maintenance, plug-and-play solutions. Unlike conventional turbines, which require skilled technicians for installation and upkeep, these systems can be quickly deployed with minimal oversight. Their enclosed or bladeless designs also enhance safety in temporary settlements by eliminating exposed moving parts. However, depending on the subtype, some noise concerns may still arise. Relevant stakeholders for development are Ventum dynamics, Halcium, Vortex Bladeless, Aeromine Technologies, Katrick Technologies, Fraunhofer Institute for Wind Energy Systems (IWES), European Academy of Wind Energy (EAWE), Technical University of Denmark (DTU).

3.3.4. Lithium Sulphur Batteries

Lithium-Sulphur (Li-S) Batteries deliver much higher gravimetric energy density (theoretically 2600wh/kg [342]) practically with up to 500-900 Wh/kg [343] more than lithium-ion, ca. 270 Wh/kg, thanks to sulphur-based cathodes and distinct conversion reactions. [342]. However, their lower volumetric density means they are lighter but likely bulkier than lithium-ion [344]. They also benefit from sulphur's abundance, reducing reliance on metals like cobalt and nickel. [345] Key challenges include polysulfide shuttling, rapid capacity loss, and lithium dendrite growth, implying a faster degradation but recent advances in electrode design, solid-state electrolytes, and encapsulation are paving the way for commercialization. [342,346], with a with a Gigafactory planned for 2027 [347].Hence, the technology is currently rated with a Technology Readiness Level of 6-7 but with a potential TRL 8-9 by 2030.

Li-S batteries also offer a compelling advantage for emergency response operations, particularly in scenarios where lightweight, high-energy-density power sources are essential. Their superior gravimetric energy density makes them well-suited for person-portable energy storage, remote emergency camps, and drones, where minimising weight can be critical. Relevant stakeholder for development are Lyten, Monash University, Fraunhofer Institute for Material and Beam Technology (Fraunhofer IWS, Germany), Helmholtz Institute Ulm (HIU, Germany), The Faraday Institution with its Lithium-Sulfur Technology Accelerator, Swiss Federal Laboratories for Materials Science and Technology, CEA-Liten, Johnson Matthey, LG, Zeta Energy.

3.3.5. Metal-Air Batteries

Metal-Air Batteries generate electricity by reacting metals with oxygen from ambient air, eliminating the need for a stored oxidiser and enabling much higher energy densities than lithium-ion batteries [348–350]. Chemistries include zinc-air, aluminium-air, iron-air, lithium-air, and magnesium-air, each with distinct characteristics Their key advantages include high energy density (exceeding 1000Wh/kg), inherent safety, and abundant electrode materials, but challenges in rechargeability, cycle stability, and power density [348–350]. Unlike lithium-ion batteries, they lack flammable organic electrolytes, reducing thermal runaway risks. Currently, only zinc- [351]air is commercially available in a non-rechargeable form, while rechargeable variants at TRLs 3–6. If rechargeability challenges are overcome, they could serve as alternatives for stationary storage and niche mobile applications.

Compared to other battery technologies, rechargeable metal-air systems are not yet viable for emergency response applications due to their limited rechargeability and cycle life. While their 2 to 10 times higher energy density, lower toxicity, and cost advantages over lithium-ion batteries are promising, practical deployment depends on overcoming key technical barriers [348–350]. With advancements in electrolyte stability, electrode reversibility, and power density, they could become a viable alternative for long-duration energy storage in the future. Relevant stakeholders for development are CIC energiGUNE, Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM), SINTEF, University of Lille and University of Poitiers, Helmholtz Institute Ulm, Phinergy, Form Energy, Log 9 Materials

3.3.6. Hydrogen-Fuelled Internal Combustion Engines

Hydrogen-Fuelled Internal Combustion Engines (H2 ICEs) function by combusting hydrogen gas in modified traditional engines, providing a clean combustion process with near-zero carbon emissions, leveraging existing combustion engine technology and infrastructure [352–354]. Advantages include high thermal efficiency due to higher compression ratios, familiarity with ICE technology, and reduced global emissions, whereas disadvantages involve technical challenges such as backfiring, knocking, high NOx emissions, and the need for specialised components and safety infrastructure [353]. Currently at the development stage (TRL 6–7), H2 ICEs face critical hurdles in managing combustion stability and emissions. Comparatively, fuel cells offer quieter operation and less heat and produce no NOx emissions contributing to health issues.

H2 ICEs could offer reliable power for vehicles, portable generators, and equipment such as lights and communication devices. However, their practicality is contingent upon resolving infrastructure and fuel supply challenges, safety measures, and managing operational complexities. Fuel cells currently offer superior operational simplicity, lower maintenance, and cleaner emissions, albeit with higher initial infrastructure investment.

3.3.7. Methanol

Methanol (CH_3OH) is considered a possible alternative fuel for internal combustion engines (ICEs) as part of global carbon neutrality efforts. Compared to fossil fuels, it offers several advantages, including a high oxygen content, a high-octane number, low cost, and easy handling. Methanol can be produced either from fossil sources such as natural gas and coal or as renewable methanol, which is synthesised from biomass (bio-methanol) or through the combination of captured CO_2 and green hydrogen (e-methanol). The power-to-liquid (PtL) technology used for methanol production enables the utilization of renewable energy sources such as wind, solar, hydro, or geothermal power. One of methanol's advantages is its high oxygen content which enhances combustion efficiency and reduces soot formation, making it an environmentally friendly option. Methanol also contains no sulphur and has a lower calorific value than conventional fuel, resulting in lower NOx emission. Additionally, methanol remains in a liquid state under standard conditions, which simplifies storage, transport, and distribution, while its versatility allows its use not only as a fuel for combustion engines but also in fuel cells and chemical processes [355–357].

However, methanol faces several challenges that need to be addressed before widespread adoption. Cold start difficulties arise due to its high heat of vaporization, making engine ignition problematic at low temperatures. Its lower energy density compared to gasoline or diesel results in increased fuel consumption, which can impact overall efficiency. Another concern is the presence of unregulated emissions, such as formaldehyde, which necessitate effective catalytic converters for mitigation. Furthermore, the production of green methanol remains costly, as it depends on the availability of renewable energy and efficient CO_2 capture technologies [355,356].

Currently, numerous prototype projects around the world are exploring large-scale methanol production. Iceland hosts one of the world's largest electrolysis and methanol plants operated by Carbon Recycling International (CRI). Sweden's Liquid Wind initiative aims to establish multiple e-methanol production facilities to supply the shipping industry. In Norway, Swiss Liquid Future and Thyssenkrupp are working on a large-scale methanol production project using CO_2 from a ferrosilicon plant. Germany is home to several power-to-methanol initiatives, including Dow's large-scale project and the MefCO2 initiative, which synthesises methanol from captured CO_2 and excess electricity [356].

3.4. Emerging lowly promising technologies (ELPETs)

The technologies can be divided into three categories: Many patents (more than 10,000), these technologies are already well established. Moderate number of patents (more than 2,000), these technologies are in application and show promising approaches. Few patents (under 500), these technologies are still heavily research-driven or considered less promising (see Annex 1).

Among the technologies in the first category are **supercapacitors**, which are primarily driven by China. Interestingly, Politechnika Poznanska is the organization with the second-highest number of active patents in this field.

In the second category, we find technologies such as **flywheel (mechanical energy storage)** and **compressed air energy storage (CAES)**, both of which are exclusively dominated by China. In the case of E-Ammonia, Switzerland, represented by **Casale SA**, and Germany's **Thyssenkrupp AG** are also leading.

The third category includes technologies with few patents, such as **Carnot batteries**, which are also driven by China, as well as **E-fuels**, where Germany, represented by *Daimler AG*, plays a leading role. Generally, a significant number of patents are attributed to the automotive industry. In the field of **tidal energy generators**, alongside China, South Korea and Finland are also active. In the areas of **small modular (nuclear) reactors and liquid organic hydrogen carriers**, South Korea is leading. Interestingly, Saudi Arabia holds the second position in **liquid organic hydrogen carriers**, while France occupies a top position in Europe. Several German companies, such as *N-Ergie AG* and *Hydrogenius Lohc Technologies GmbH*, are also active in this field. With only 50 patents, **pedal-powered generators** are hardly present in application-driven research, with Japan, led by *Shimano Inc*., at the forefront.

3.4.1. Small Modular (nuclear) Reactors

Small Modular Reactors (SMRs) are nuclear reactors with electrical outputs of up to 300 MW [358], while a subset, microreactors (MRs) or very small SMRs (vSMRs), typically range from 1 to 20 MW and can be either stationary or mobile [359]. Their compact size allows for modular factory construction and transportability, reducing build times and improving quality control [359]. Passive and active safety features minimise the risk of major radioactive releases, and deployment options include land-based, multi-module, or floating units, such as ship or truck-mounted reactors [360]. SMRs offer scalability, a stable energy supply, and a smaller emission footprint, but regulatory, waste management, and ethical challenges remain significant hurdles [360–363]. Despite being designed for factory assembly and transport as modules or even whole units, economic feasibility remains uncertain, as most designs are still far from commercialization [364]. Currently classified at Technology Readiness Level (TRL) 4, they are projected to reach TRL 5-7 by 2030.

For emergency response organizations, microreactors (MRs) and mobile nuclear power plants (MNPPs) could provide long-term, off-grid power in disaster zones or remote areas where renewables are insufficient. However, as most SMRs remain in the conceptual or early development stage, regulatory, logistical, and safety barriers hinder rapid deployment, limiting their short-term practicality in emergency scenarios.

3.4.2. RTidal Energy Generators

Tidal Energy Converters (TECs) generate electricity by harnessing the kinetic and potential energy of tidal currents, driven by the moon's gravitational pull and Earth's rotation [365–368]. Unlike wind and solar power, tidal energy follows a fixed, regular cycle, making it one of the most predictable renewable sources [365–368]. TECs operate like wind energy converters but in an underwater environment, where water's higher density (800 times that of air) allows for smaller, more efficient units that function even at low flow speeds [365–368]. They can be installed on the seabed or as floating platforms, enabling deployment in remote coastal and island communities [365–368]. Depending the unit size, they have range of capacity of 100kW [369] to 2,4 MW [370], 10 hours [371] or even longer a day. However, TECs require strong tidal flows, limiting their applicability to specific locations.

Most TECs are less mobile than other low-emission energy technologies. While some can be transported by ship to the desired location, they require precise underwater positioning and secure anchoring. These factors limit their practicality for rapid deployment, easy installation, and maintenance, making them less suitable for emergency response organizations despite their high reliability.

3.4.3. Pedal-Powered Generators

Pedal-Powered Generators harness human kinetic energy to produce electricity, offering a decentralised and sustainable power source. These systems convert mechanical energy from pedalling into electrical energy via a generator, which can be used directly or stored in batteries. A fit individual can generate around 150–200 W while cycling, sufficient for charging small devices, powering lighting, or supplementing household energy needs [372–376].

Efficiency depends on generator type, mechanical design, and energy transmission. A stationary bike generator with a brushless DC motor generates 12V–14V at optimal speeds with a belt ratio of 8:1. At 200 RPM, it produces 11–12V at 10.46A, reaching 13.5–14.5V at 250 RPM. A chain sprocket and belt mechanism improve energy conversion, while a flywheel-based system stabilizes power output [372–374]. Some systems generate up to 114 W, sustaining multiple devices like mobile phones and laptops for over four hours [375].

These generators have practical applications in off-grid and urban settings. In rural areas, they provide electricity for lighting, mobile charging, and small appliances. In India, school-based systems allow ten minutes of pedalling to generate forty minutes of light [373]. In cities, they integrate into fitness equipment, promoting exercise while generating power [372,374,376]. Public spaces such as parks also utilize them for device charging [375].

Despite benefits, limitations include low energy output and reliance on human effort. They are unsuitable for high-power applications, and mechanical inefficiencies reduce overall efficiency. Hybrid systems combining pedal power with solar or wind energy could improve practicality. Future advancements in flywheel storage, regenerative braking, and optimized transmission may enhance efficiency and expand applications [372,374–376].

3.4.4. Liquid Organic Hydrogen Carriers

Liquid Organic Hydrogen Carriers (LOHCs) offer a promising solution for hydrogen storage and transport at ambient conditions, overcoming challenges related to compression and liquefaction. LOHCs, such as methylcyclohexane (MCH)/toluene and perhydro-dibenzyltoluene (H18-DBT)/dibenzyltoluene (DBT), enable reversible hydrogenation and dehydrogenation without producing by-products. This allows for efficient storage, long-distance transport using existing fuel infrastructure, and controlled hydrogen release where needed.

The advantages of LOHCs include high storage density, safety, and compatibility with current energy infrastructure, reducing transportation costs and risks. However, a major drawback is the high energy demand for dehydrogenation, requiring temperatures of 250–350°C, leading to efficiency losses, catalyst deactivation, and potential LOHC degradation [377]. Research is focused on improving catalysts, process heat integration, and optimising reactor design to address these challenges.

Currently, LOHC technology is under pilot demonstration in countries like Japan and Germany. Companies such as Chiyoda Corporation and Hydrogenious Technologies are testing LOHC systems for large-scale hydrogen transport and stationary applications. LOHCs are especially attractive for off-grid applications, such as emergency shelters and bases of operation. In these cases, LOHCs can store surplus renewable energy in the form of hydrogen, which can later be released and converted back into electricity. Economic analysis suggests that off-grid applications of LOHCs can compete with diesel generators, particularly in remote areas with high fuel costs and especially as the costs of renewable energy continue to decline. Despite their potential, widespread adoption depends on further technological advancements to improve efficiency and economic viability [99,101,377–379].

3.4.5. E-Fuels

E-fuels, or electrofuels, are synthetic fuels produced using renewable energy. They are considered a key technology for decarbonising transportation and industry, as they provide an alternative to fossil fuels while enabling carbon recycling. The core components of e-fuel production include hydrogen (e-H_2), generated through water electrolysis using renewable electricity, and carbon dioxide (CO_2), captured from industrial emissions, biomass combustion and biogas production or directly from the air (DAC). E-hydrogen can be combined with CO_2 to create e-methanol, e-methane, e-diesel, and other fuels, or with nitrogen to produce e-ammonia [356].

The advantages of e-fuels include their high energy density, easy storage and transportability, and compatibility with existing internal combustion engines (ICEs), reducing the need for new infrastructure (e.g. for e-diesel, e-gasoline, e-kerosine or e-methanol). They can also serve as long-term energy carriers, balancing fluctuations in renewable electricity generation. However, from electricity to e-fuel, there is about a 40% loss [380]. The current high cost of green hydrogen and CO_2 capture also makes e-fuels significantly more expensive than fossil fuels. Currently, e-fuels can cost up to EUR 7 per litre, but prices are expected to fall due to economies of scale and declining renewable electricity prices, potentially reaching EUR 1 to EUR 3 per litre by 2050 (excluding taxes) [380]. Future cost reductions in electrolysis and carbon capture technologies, along with expanding renewable energy capacity, could improve their competitiveness. While currently costly and energy-intensive, e-fuels offer a promising pathway for sustainable fuel production in a low-carbon economy [356,357,380].

3.4.6. E-Ammonia

E-ammonia is a synthetic fuel produced by combining green hydrogen (generated via water electrolysis using renewable energy) with nitrogen, which is extracted from the air. The nitrogen is captured from ambient air with three possible technologies: cryogenic separation, pressure swing adsorption (PSA), and membrane permeation. For large-scale ammonia plants, cryogenic distillation is the more convenient option due to the lowest specific consumption which is equal to 0.11 kWh/kgN2 [381]. This process follows the Haber-Bosch method, where hydrogen and nitrogen react under high pressure and temperature using an iron-based catalyst. Unlike conventional ammonia, which is derived from fossil fuels, e-ammonia is carbon-free and considered a promising energy carrier for decarbonization [356].

One key advantage of e-ammonia is its high hydrogen content, making it an efficient fuel for internal combustion engines (ICEs) [356]. Additionally, it can be stored and transported more easily than hydrogen, providing a stable energy supply [357]. It can also be blended with other fuels, such as diesel, to enhance combustion performance and reduce carbon emissions [382].

However, e-ammonia production is energy-intensive and costly, largely depending on the price of green hydrogen and nitrogen separation. Safety concerns also arise due to ammonia's toxicity and corrosiveness, requiring strict handling and storage measures [356]. Moreover, its combustion characteristics, such as high ignition energy and low flammability [381], pose technical challenges for engine adaptation.

Despite these challenges, e-ammonia has great potential as a clean fuel and hydrogen carrier. With advancements in renewable energy and electrolysis technology, production costs are expected to decrease, making e-ammonia a viable solution for reducing carbon emissions in various industries.

3.4.7. Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) is an energy storage technology that helps balance fluctuations in renewable energy supply by compressing air and storing it in underground caverns or high-pressure tanks. When energy is needed, the compressed air is expanded through turbines to generate electricity. Traditional large-scale CAES, such as those in Huntorf, Germany, and McIntosh, USA, follow a diabatic process in which compression heat is lost and fossil fuels are required for reheating, limiting efficiency to 42–54% [383]. Advanced adiabatic CAES (A-CAES) improves efficiency beyond 70% by capturing and reusing this heat, eliminating the need for fossil fuel combustion [384].

Optimising the number of compression and expansion stages significantly impacts CAES efficiency and economic feasibility. Research on Advanced Adiabatic CAES with Combined Heat and Power (AA-CAES-CHP) shows that increasing the number of compression and expansion stages reduces exergy losses and improves system performance. While five-stage configurations provide greater thermodynamic advantages over three-stage systems, excessive stage numbers lead to diminishing efficiency gains and higher capital investment [385]. Hybrid CAES designs, such as Supercritical CAES (SC-CAES), Underwater CAES (UCAES), and Liquid Air Energy Storage (LAES), are also being explored to enhance energy density and storage flexibility by leveraging extreme pressures, deep-sea reservoirs, and air liquefaction technologies [384].

Smaller-scale CAES systems, including mini-CAES below 10 MW and small-scale CAES between 10 and 100 MW, are gaining attention for distributed energy storage, microgrids, and industrial applications. Unlike large-scale CAES, these systems store air in high-pressure tanks, making them viable in urban settings and remote locations. However, mini-CAES faces challenges such as heat losses, lower energy density, and limited financial feasibility. Studies suggest that integrating these systems with combined heat and power (CHP) applications and using scroll or reciprocating expanders could improve efficiency by capturing and utilising waste heat [386].

Compared to battery storage, CAES offers longer lifespans, lower degradation rates, and reduced reliance on rare materials. While large-scale CAES requires specific geological conditions and small-scale systems face efficiency and cost barriers, CAES remains one of the most cost-effective long-duration storage solutions. Future developments include hybridization with waste heat recovery, hydrogen storage, and renewable energy sources to improve efficiency and market competitiveness [383,385]. As advancements continue, both large-scale and small-scale CAES are expected to support the transition to a low-carbon energy system.

3.4.8. Supercapacitors

Supercapacitors, also known as ultracapacitors or electrochemical capacitors, are energy storage devices with high power density, fast charge-discharge rates, and long cycle life. Unlike batteries, which store energy through chemical reactions, supercapacitors rely on electrostatic charge storage via electric double-layer capacitance (EDLC) or pseudocapacitance. EDLC supercapacitors use carbon-based materials like activated carbon or graphene, while pseudocapacitive supercapacitors involve Faradaic reactions with transition metal oxides (e.g., MnO_2, RuO_2) or conducting polymers (e.g., polyaniline, polypyrrole) [387,388].

Supercapacitors are widely used in applications requiring rapid energy bursts, such as regenerative braking in electric vehicles and grid stabilization for renewable energy. Their advantages include ultra-fast charging, high efficiency, and durability exceeding one million charge cycles. However, they suffer from lower energy density (5–30 Wh/kg) compared to lithium-ion batteries (150–250 Wh/kg), limiting their ability to store energy for extended periods [387,389].

Advancements in materials science aim to overcome these limitations. Graphene-based supercapacitors improve conductivity, surface area, and capacitance retention. The integration of conducting polymers and redox-active organic molecules, such as quinones, enhances energy storage by introducing reversible redox reactions. Additionally, hybrid supercapacitors combining EDLC and pseudocapacitive mechanisms offer a balance between power and energy density [388,389].

Flexible and wearable supercapacitors have emerged as promising energy storage solutions for next-generation electronics. Materials like three-dimensional graphene-polyaniline composites and polypyrrole hydrogels provide improved mechanical flexibility while maintaining high capacitance. Textile-based electrodes coated with graphene and conducting polymers enable durable and lightweight supercapacitors for wearable applications [389].

As research continues, the development of novel electrode materials, such as MXenes and metal-organic frameworks, alongside advanced electrolytes like ionic liquids, is expected to enhance supercapacitor performance. With increasing demand in electric mobility, consumer electronics, and renewable energy storage, supercapacitors are positioned to complement or even replace batteries in high-power applications, driving sustainable energy innovations [387–389].

3.4.9. Carnot Batteries

A Carnot Battery is a thermal energy storage system that converts electricity into heat, stores it, and later reconverts it into electricity. It is considered a promising large-scale storage solution for balancing renewable energy fluctuations and enabling decarbonization [390]. Unlike conventional batteries, it relies on cost-effective and widely available materials such as molten salts, ceramic blocks, or packed-bed rocks. Electricity is first converted into heat using resistive heating, heat pumps, or thermodynamic cycles like Rankine or Brayton cycles [391]. The heat is stored in a medium such as molten salts, solid particles, or compressed air, chosen based on heat capacity, cost, and stability [392]. When energy is needed, the stored heat drives turbines or thermodynamic cycles to produce electricity.

Carnot batteries offer advantages such as scalability, geographic flexibility, and cost-effectiveness. They integrate well with industrial waste heat recovery and district heating, increasing overall efficiency [391]. Their long lifespan, estimated at 20–30 years, surpasses that of electrochemical batteries [390]. However, efficiency constraints remain a challenge, as round-trip efficiency ranges between 40% and 70%, depending on the thermodynamic cycle and storage medium [392]. While some systems, such as Siemens Gamesa's ETES and Highview Power's liquid air energy storage, are in pilot or commercial operation, many technologies are still under development [390]. Large-scale implementation requires significant infrastructure investment, though costs are expected to decline with further advancements [391].

Current developments focus on integrating Carnot batteries with renewable power plants, industrial processes, and hybrid energy storage solutions. Companies such as Highview Power, Malta Inc., and Siemens Energy are advancing various configurations, including cryogenic air storage and Brayton-cycle-based systems [392]. European and Australian projects are actively exploring their real-world viability [390]. With further improvements in heat storage materials and thermodynamic efficiency, Carnot batteries are expected to play a crucial role in long-duration energy storage and grid stability [391].

3.4.10. Flywheel Energy Storage

Flywheel Energy Storage (FES) stores energy as rotational kinetic energy using a spinning mass powered by an electric motor [393–396]. It consists of an Energy Storage Module (ESM) to accelerate the flywheel and an Energy Conversion Module (ECM) to generate electricity. Key advantages include rapid response times, long cycle life, high efficiency (80-90%), and no capacity degradation. However, downsides include noise, sensitivity to vibrations, and relatively high self-discharge (2-20% per hour), limiting its effectiveness for long-term storage [394,396,397]. Compared to batteries, FES enables faster charge-discharge cycles and greater durability but retains energy for only minutes to a few hours due to its high self-discharge rate, making it better suited for high-power, short-term applications [394] [393–396]. While vacuum-sealed and underground installations could help mitigate some challenges, high costs, weight, and energy density constraints limit widespread adoption [393,397]. Their Technology Readiness Level is quite high with 8 but for short-term-storage.

For emergency response organizations, FES offers instant power stabilization, rapid deployment, and seamless integration with renewable energy sources. Containerized systems can be quickly transported to disaster zones, providing high-power, fast-response energy discharge [394,396]. However, their sensitivity to movement limits their suitability for highly mobile operations. Despite this, FES can be effectively integrated into hybrid energy storage systems, enhancing grid stability and serving as a high-efficiency short-term backup power source in emergency scenarios.

4. Holistic systems and stakeholders

Based on input from Powerbase partners, inquiries received via LinkedIn and our website, as well as our own research, we have identified the following system solutions relevant for mobile low-emission energy supply. This list includes twenty solutions both hybrid systems and fully renewable, solutions or products (see Table 51).

Table 51: Overview Holistic System Provider

Product Name	Company/ Actor	Description	Link
Hybrid Solar Generator Systems	Volta Energy	Mobile hybrid solar generators providing sustainable energy solutions for various applications.	https://volta-energy.com/en/hybrid-solar-generator-systems/
Sesame Solar Mobile Nanogrids	Sesame Solar	Mobile solar nanogrids designed for rapid deployment in disaster response scenarios.	https://www.sesame.solar/
Mobile Energy Storage Power Vehicle	Tecloman	Vehicles equipped with energy storage systems for mobile power supply.	https://www.tecloman.com/product/mobile-energy-storage-power-vehicle/
Sun Titan™ Power Trailer	RPS Solar Pumps	Off-grid power plant featuring solar, battery, and diesel backup on a trailer.	https://shop.rpssolarpumps.com/products/off-grid-power-plant-solar-battery-diesel-backup-trailer
SCT-20 Mobile Solar Generator with Light Towers	CleanAir Engineering	Mobile solar generator equipped with light towers for illumination and power supply.	https://www.cleanair.com/product/sct-20-mobile-solar-generator-with-light-towers/
Hybrid Solar Trailer	Homestead Hybrid	Solar trailer offering 12,000W output with 30kWh storage and 11kW backup generator.	https://www.homesteadhybrid.com/products/hybrid-solar-trailer-12-000w-output-30kwh-of-storage
Mobile Emergency Response Vehicle	United Energy	Vehicle designed to support local communities during emergencies with mobile power.	https://www.unitedenergy.com.au/media-centre/new-mobile-emergency-response-vehicle-to-support-local-communities/
The Nomad System	Nomad Power	Mobile energy supply units ranging from 214 kWh to 2 MWh capacities.	https://www.nomadpower.com/products
Energy Container for Self-Sufficient & Hybrid Emergency Power Supply	SFC Public Security	Energy containers providing self-sufficient and hybrid power supply for disaster management.	https://www.sfc-publicsecurity.com/en/energy-container-for-self-sufficient-hybrid-emergency-power-supply-in-civil-protection-and-disaster-management/
ContainerHybrid	MobilHybrid	Containerized power supply offering flexible and powerful energy systems.	https://mobilhybrid.de/en/containerhybrid-2/
MH 108	MobilHybrid	Mobile hybrid power system with a 108 kWh battery storage capacity, designed for efficient and sustainable power supply.	https://mobilhybrid.de/en/product/mh-108/
Mobile Battery Energy Systems	Generac Mobile	Mobile battery energy storage units designed for various applications.	https://www.towerlight.com/mobile-battery-energy/

Hybrid Power Systems	VINCORION	Hybrid energy systems integrating diesel generators with battery storage and renewable sources for emergency and military use.	https://www.vincorion.com/wp-content/uploads/2022/04/241007_VINC_DB_SEA_PGM_ESM_DE_DINA4_Web-1.pdf
Solartainer	Africa GreenTec	Mobile, scalable solar energy solution providing off-grid power with integrated storage for sustainable electricity in remote and emergency situations.	https://www.africagreentec.com/impactproducts/solartainer/
Hybrid Bio Solar Generators	mobilespace	Environmentally friendly, self-sufficient solar trailers offering up to 45 KVA power with integrated battery storage.	https://www.mobilespace.de/en/rental/rental-vehicles/power-generator
Hybrid Generators	The Green Generators	Innovative hybrid generators utilising solar panels, achieving up to 95% lower fuel usage and CO_2 emissions	https://thegreengenerators.com/
hybrid Wind-Diesel Power Plant (Faroe Islands)	MAN Energy Solutions	Hybrid power system integrating wind energy with diesel backup for stable and reliable energy supply in remote locations.	https://www.man-es.com/energy-storage/solutions/hybrid-power
Genesal Energy Solutions	Genesal Energy	Provides hybrid-power solutions for emergency, industrial, and defense applications	https://genesalenergy.com/en/
Lithium Power Supply (LPS) II Kit 2 with Inverter and Panels	Clayton Power	All-in-one lithium power system featuring an inverter and solar panels, designed for mobile applications like service vehicles and off-grid operations.	https://www.claytonpower.com/de/losungen/automobilindustrie/wartungsfahrzeuge/#
SmartFlower+ PLus	Smartflower	It provides a powerful, fully integrated battery system that delivers clean energy anytime, ideal for off-grid use, achieving up to 100% energy self-sufficiency, and offering reliable backup power during outages	https://smartflower.com/products/?lang=de

The researchers conducted a preliminary, subjective assessment of the holistic solution after the performance requirements had been defined. Although many providers claim to offer low-emission alternatives to diesel generators, none of the solutions presented in the table fully satisfied the comprehensive ERO functional and performance requirements. Most approaches addressed only specific aspects or individual components of an energy system, thereby underscoring a research and development gap in the provision of suitable mobile energy supply systems for EROs.

For more detailed and scientifically rigorous investigation, these holistic systems and their corresponding suppliers were added to the supplier list and communicated to WP3, with the objective of inviting them to the OMC events to present their solutions. They were also invited to participate in the self-evaluation Supplier Survey. The results of this process are presented in Chapter 5 and Annex 2.

5. SOTA-Analysis

The present analysis has combined two distinct but complementary strands of evidence in order to provide a structured overview of the state of the art in sustainable, low-emission, and compact energy supply technologies for emergency response operations. On the one hand, the supplier survey conducted in August 2025 gathered responses from companies regarding the compliance of their products with a condensed set of functional and performance requirements. On the other hand, technology fact sheets were prepared to map the broader spectrum of (possibly) relevant energy technologies at the level of technology classes rather than individual products (see Figure 7).
The two approaches serve different functions. The survey provides a market-oriented picture, offering insights into which providers are present, how they perceive their own products in relation to operational needs and requirements, and where gaps may exist. However, because the survey was based on self-reporting, the responses remain heterogeneous and not yet validated. It is planned to validate these statements in following PCP project.
The fact sheets, by contrast, offer a systematic comparison of technology classes along requirement clusters, providing ranges of performance metrics, typical advantages and limitations, and indicative assessments of maturity. They do not focus specific commercial solutions (display some only as examples for the spectrum), but they can contextualise the survey results by situating them within a broader technological landscape. Taken together, the two strands of evidence create a complementary basis for the preparation of a potential subsequent PCP process.

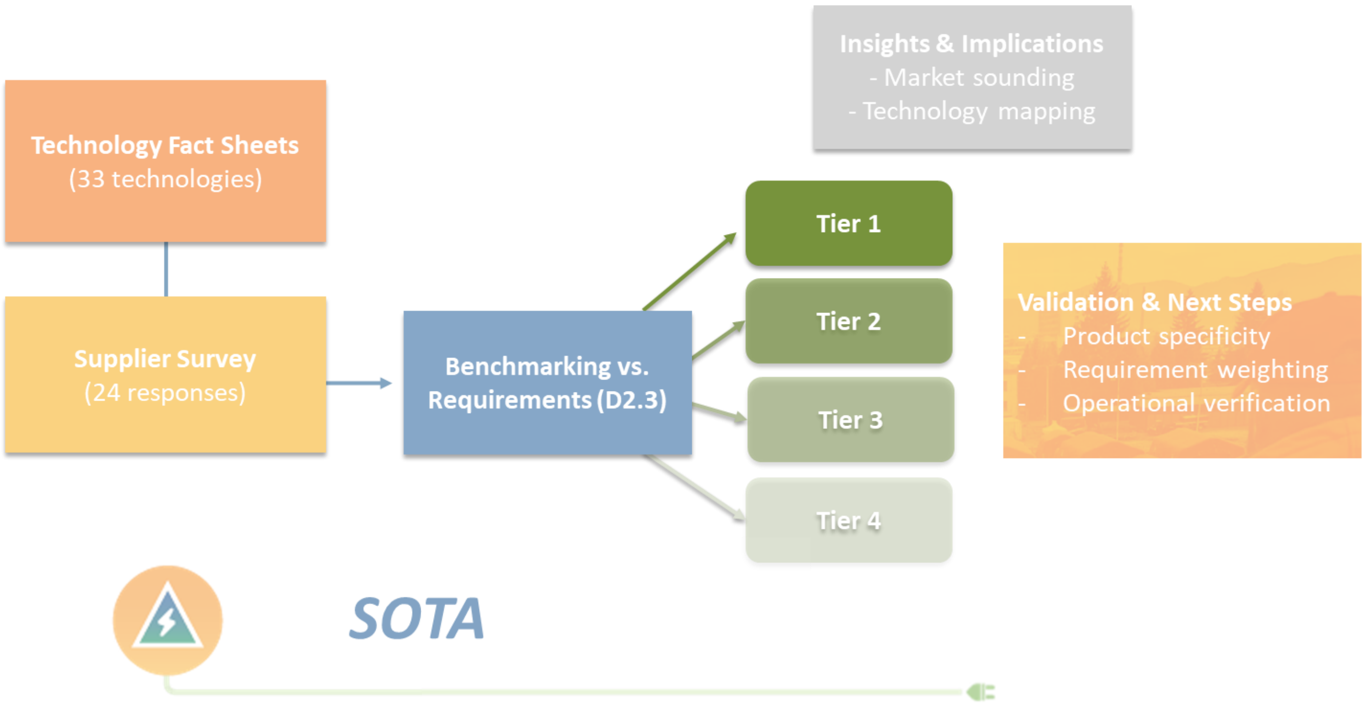


Figure 7: SOTA Analysis Overview

5.1. Supplier Survey Analysis

Disclaimer
The following survey results, are part of the State-of-the-Art (SOTA) analysis, present information on selected products and providers currently available on the market. The information is based on survey responses as provided in the following chapters (and in Chapter 2.5).

The inclusion or omission of a company or product does not imply any form of endorsement, recommendation, or rejection by the project consortium. The list reflects only those products for which providers submitted responses to the survey. The survey was sent out to all companies that have been identified during the project phase (especially as part of the SOTA and the OMCs). The purpose of this analysis is solely to assess available solutions in relation to the performance and technical requirements identified in D2.3. Solutions may evolve over time, and providers not mentioned here may also offer relevant technologies.

5.1.1. Results

The table below provides an overview of the compliance with requirements and percentage for each product, based on 24 survey responses for the product by the respective companies (see Table 52). For a detailed overview of responses, see Table 53).
The outcomes are anonymised as this deliverable is a publicly available document. This approach ensures the protection of commercially sensitive information and avoids the unintended disclosure of company-specific performance data. While a non-anonymised version of the results is stored, as described in the data protection protocols, the anonymisation in the public deliverable safeguards supplier interests, prevents potential misinterpretation of individual results outside their technical context, and maintains a neutral position of the project consortium toward specific providers. The survey results are based on the 18 questions listed in Chapter 2.5, which were derived from the functional and performance requirements defined in Deliverable D2.2.

Table 52: Overview Survey Results (absolute and rate)

Product	Total Requirements	Covered	Not Covered	Not Applicable	Coverage Rate
Technology 1	18	18	0	0	100.0
Technology 2	18	17	1	0	94.4
Technology 3	18	17	1	0	94.4
Technology 4	18	17	1	0	94.4
Technology 5	18	17	1	0	94.4
Technology 6	18	16	2	0	88.9
Technology 7	18	16	1	1	88.9
Technology 8	18	16	2	0	88.9
Technology 9	18	15	2	1	83.3
Technology 10	18	15	3	0	83.3
Technology 11	18	15	2	1	83.3
Technology 12	18	15	0	3	83.3
Technology 13	18	14	3	1	77.8
Technology 14	18	14	4	0	77.8
Technology 15	18	14	2	2	77.8
Technology 16	18	13	5	0	72.2
Technology 17	18	13	4	0	72.2
Technology 18	18	13	4	1	72.2
Technology 19	18	13	5	0	72.2
Technology 20	18	13	3	2	72.2
Technology 21	18	12	5	1	66.7
Technology 22	18	12	4	2	66.7
Technology 23	18	12	5	1	66.7
Technology 24	18	8	1	5	44.4

The survey responses indicated a heterogeneous degree of self-reported compliance with the clustered requirement set (see Table 53). Reported coverage rates ranged from 44% to 100%, reflecting substantial diversity in product maturity, specificity, and the way in which companies interpreted the survey questions.

At the upper end of the distribution, Technology 1 reported full self-declared compliance with all 18 assessed requirements (100%). Several further entries, Technology 2, Technology 3, Technology 4, and Technology 5, reported compliance with 17 of 18 requirements (94.4%). These submissions, on a self-declared basis, suggest near-comprehensive coverage of the condensed requirement clusters.

A second group of responses, including Technology 6, Technology 7, and Technology 8, reported compliance with 16 of 18 requirements (88.9%). These entries indicate broad but not complete coverage and highlight potential gaps that would require clarification in subsequent validation.

The broader mid-range of reported compliance (72–83%, equivalent to 13–15 requirements covered) includes Technology 9, Technology 10, Technology 11, Technology 12, Technology 13, Technology 14, Technology 15, Technology 16, Technology 17, Technology 18, Technology 19, and Technology 20. These results point to partial but indicative alignment with the requirements, suggesting promising directions for further investigation but not yet comprehensive coverage.

At the lower end of the distribution, Technology 21, Technology 22, and Technology 23 reported compliance levels of 66.7% (12/18). The lowest reported coverage was observed for Technology 24, with 44.4% (8/18). Such results may reflect either narrower product design intent or incomplete mapping to the requirement framework rather than intrinsic unsuitability.

Table 53: Overview Survey Results (by questions)

Technology	Q1[14]	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18
Technology 1	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 2	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 3	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 4	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 5	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 6	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 7	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡
Technology 8	🟢	🔴	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 9	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟡	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 10	🟢	🟢	🟢	🟢	🔴	🟢	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 11	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🔴	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 12	🟡	🟡	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 13	🟢	🟢	🔴	🔴	🔴	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 14	🟢	🟢	🟢	🟢	🔴	🟢	🔴	🔴	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 15	🟢	🟢	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 16	🟢	🔴	🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🔴	🟢	🟢
Technology 17	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🔴	🟢	🔴
Technology 18	🔴	🔴	🔴	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 19	🟢	🔴	🔴	🔴	🔴	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 20	🔴	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🔴	🟡	🟢	🟢	🟢	🟢	🟢	🟡
Technology 21	🔴	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🔴	🟡	🟢	🟢	🔴
Technology 22	🟡	🟢	🟢	🟢	🟡	🟢	🔴	🔴	🟢	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 23	🔴	🔴	🔴	🟢	🔴	🟢	🟢	🟡	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Technology 24	🟢	🔴	🟢	🟢	🟢	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟢	🟢

Legend:
- 🟢 Compliant (requirement covered)
- 🟡 Partial/unclear or not applicable
- 🔴 Not compliant

[14] See Chapter 2.5 for the respective questions.

Taken together, the survey illustrates that the market already provides a variety of solutions which, on a self-reported basis, appear to align with a substantial portion of the operational requirements. At the same time, the heterogeneity of the responses and the lack of independent validation underscore the need for further clarification rounds and technical assessment. In terms of a potential PCP, the survey thus functions as an exploratory market sounding: it identifies potential candidates and indicates levels of maturity, but it cannot yet serve as evidence of verified performance.

The responses of the 24 suppliers were further examined to identify which functional requirements were least frequently reported as fulfilled. The requirements most often indicated as unmet (reported as "not fulfilled" by more than ten suppliers) were:

- Energy conversion system supports commercially available fuel
- Product is suitable for deployment on commercial aircraft
- Product combines energy generation, conversion, and storage

In a subsequent PCP project, the development of products will therefore need to focus in particular on advancing solutions towards the combination of energy generation and storage, transportability by commercial aircraft, and support for commercially available fuels.

In contrast, several requirements were reported as fulfilled by all suppliers, including:

- System is designed for easy transport
- System is designed for rapid deployment
- System can maintain full functionality under harsh environmental conditions (e.g., heat, humidity, dust)
- System is designed for low-maintenance operation and easy servicing in the field
- System ensures the safety of personnel, equipment, and the environment during all phases of use (deployment, transport, installation, operation, maintenance)
- System is designed to operate with minimal noise emissions (e.g., dB(A))

However, these positive responses should be interpreted with caution. For example, although many suppliers stated that their systems are designed for rapid deployment, a number of these solutions cannot be transported on commercial aircraft. This indicates that some requirements may be met only under certain conditions or with important limitations, and that "rapid deployment" does not necessarily imply full compliance with all associated logistical constraints.

5.1.2. Interpretation of Results

Several responses were not product-specific in a strict sense. For example, Technology 5 referred to "more than one product" in a single entry; Technology 21 described "several products based on hydrogen technologies;" and Technology 13 outlined a future concept rather than a commercial product. Such submissions reduce comparability with the survey's intent, which was to identify single, deliverable products that independently cover the requirement set without relying on unspecified combinations.

Because the ranking is derived from self-reported inputs, some tightly product-bound, others more capability- or concept-oriented, thus again the percentages should be interpreted as indicative signals rather than validated performance evidence guiding a potential PCP project. This is particularly relevant at both ends of the distribution: very high values (e.g. 100% for Technology 1) reflect complete self-declared conformity, while lower values (e.g. 44.4% for Technology 24) may reflect narrower design intent or incomplete mapping against the requirement framework. These outcomes do not necessarily imply intrinsic suitability or unsuitability, but rather differences in how products and concepts were positioned against the clustered requirement set.

5.1.3. Methodological Limitations & Conclusion

The survey yielded a heterogeneous dataset covering a broad range of technologies, from photovoltaic systems and small hydro turbines to lithium-ion batteries, hydrogen storage, fuel cells, micro gas turbines, and biomass-based solutions. The responses were systematically captured in tabular form, and the aggregated values (covered, not covered, and not applicable requirements) provide a first indication of the potential alignment between the surveyed technologies and the defined technical and functional requirements.

Several methodological limitations must be highlighted in order to appropriately interpret the results:

1. **Product-specificity**: In several cases, respondents did not name a single, identifiable product but instead described broader capabilities, sometimes referring to families of products or concepts. This reduces comparability with the intended survey design.
2. **Requirement weighting**: All requirements are relevant in principle, but their operational significance is not uniform. Certain criteria (e.g. modularity, safety, rapid deployability) are of central importance and should be prioritised in future evaluations. Establishing a preference matrix that distinguishes between core and secondary requirements is therefore recommended.
3. **Validation of responses**: Because the survey relied on written self-reporting, the validity of the information submitted cannot be guaranteed. More robust insights will require direct dialogue with providers, including structured interviews with technical experts and end-users, in order to verify claims and ensure a realistic mapping to operational conditions.
4. **System-level perspective**: Many suppliers framed their contributions primarily in terms of individual components or subsystems (e.g., storage or, generation technologies) rather than fully integrated energy solutions. As a result, performance data often reflect the characteristics of isolated technologies rather than their behaviour within a holistic, deployable energy system, also making it harder to compare the outcomes.
5. **Level of detail and quantification**: Several survey questions were formulated in a binary (yes/no) manner and did not systematically request quantitative values for key performance indicators (KPIs). Consequently, the responses often lacked precision on critical parameters such as storage capacity, fuel consumption, noise levels, and performance under operational condition.

Taken together, these limitations mean that the survey provides indicative insights rather than validated evidence of suitability. The absence of consistently product-specific data, combined with the lack of requirement prioritisation, prevents a definitive ranking or selection. Nevertheless, the survey has proven valuable as an exploratory step: it has offered an overview of the provider landscape, identified gaps in the evidence base, and generated recommendations for designing future assessments in a more robust and targeted manner.

5.2. Technology Fact Sheet Analysis

The technology fact sheets provide a complementary perspective to the supplier survey by analysing technologies at the level of broader classes rather than individual products. Each fact sheet assessed typical performance parameters, operational constraints, maturity levels, and alignment with the clustered requirements. This approach does not depend on self-reported data but instead synthesises available evidence from technical literature, datasheets, and market reports. It therefore offers a structured overview of the technological landscape, identifies trade-offs inherent to each option, and clarifies which categories are more or less suited to portable, low-emission energy supply for emergency response operations.

5.2.1. Commercial Off-the-Shelf (COTS) Technologies

Several COTS technologies already demonstrate a high degree of maturity and are available in modular, deployable formats. These are most relevant for a potential PCP process.

- **Lithium-ion batteries**: Widely available in portable and containerised systems; high energy density and modular scalability. Limitations concern critical raw materials, recycling, and restrictions on air transport. Overall, they are strong candidates for inclusion as storage solution.
- **Hydrogen PEM fuel cells (portable units)**: Silent, emission-free operation makes them attractive for sensitive deployments (urban, medical). Their main constraint is hydrogen logistics, including storage and refuelling infrastructure.
- **Photovoltaics (crystalline and thin-film)**: Lightweight, noise-free, and rapidly deployable; thin-film modules in particular allow flexible expeditionary use. Limitations include surface area requirements and intermittent supply, which necessitate storage integration.
- **Hybrid battery–genset systems**: Already commercialised for expeditionary and off-grid contexts. They reduce runtime and emissions of conventional generators by covering most loads through batteries. However, peak demand still triggers noise and exhaust emissions.

Other COTS options have more conditional relevance:

- **Small wind turbines** and **small hydro generators** can contribute renewable generation in specific site conditions but are highly location-dependent.
- **Micro gas turbines** are robust and multi-fuel capable, but lower in efficiency than other technologies; are higher in noise, and exhaust complexity restrict their deployment.
- **Biomass and waste-to-energy systems** provide circular-economy benefits but depend on feedstock availability, preprocessing, and trained operators. They are better suited to long-duration stationary bases than rapid deployment.
- **Flow batteries** are durable and safe but bulky and therefore less suited for portable use.
- **Methanol-based energy systems (DMFC/APUs)** are quiet and easy to handle but currently limited to low power ranges, making them appropriate for niche applications such as communications equipment rather than whole base loads.

Taken together, the COTS category suggests a prioritisation for a potential PCP preparation: **core candidates** include lithium-ion batteries, portable PEM fuel cells, photovoltaic modules, and hybrid battery–genset systems; **site-dependent or niche options** include small wind, hydro, micro turbines, biomass, flow batteries, and methanol systems.

5.2.2. Emerging Highly Promising Technologies (EHPETs)

This category includes technologies with strong potential advantages but insufficient maturity for near-term procurement.

- **Sodium-ion batteries**: Safer and cheaper than lithium-ion, with promising sustainability characteristics; however, they currently offer lower energy density and limited COTS availability.
- **Solid-state batteries**: Potential for high energy density and intrinsic safety; currently in pilot or pre-commercial stages with unresolved cost and scalability challenges.
- **Metal hydride hydrogen storage**: Provides safe handling advantages compared to compressed hydrogen, but systems are heavy, expensive, and limited in discharge performance.
- **Wave energy converters**: Relevant in maritime or coastal contexts but site-bound and unsuitable for rapid deployment scenarios.

These technologies should be monitored and potentially piloted but cannot be considered as baseline for potential PCP solutions at this stage.

5.2.3. Emerging Moderately Promising Technologies (EMHPETs)

These technologies offer high theoretical performance but face unresolved technical barriers that limit their current applicability.

- **Perovskite and tandem photovoltaics**: High efficiency and lightweight; constrained by stability and encapsulation issues.
- **Lithium-sulfur and metal-air batteries**: Extremely high theoretical energy densities, but low cycle life and high sensitivity to environmental conditions.
- **Airborne wind and solid-state wind systems**: Innovative but unproven in terms of robustness, control, and field safety.
- **Hydrogen-fuelled internal combustion engines**: Offer a retrofit pathway using familiar mechanical systems, but efficiency, NOx emissions, and noise limit their relevance for sensitive deployments.
- **Methanol conversion systems**: Beyond current small-scale direct methanol fuel cells, methanol as a broader energy carrier remains constrained by conversion efficiencies and scaling challenges.

These technologies may become relevant in future PCP iterations or targeted innovation pilots but are not suitable for immediate procurement.

5.2.4. Emerging Lowly Promising Technologies (ELPETs)

Technologies in this category are either structurally misaligned with rapid deployment requirements or too immature to be considered beyond horizon scanning.

- **Supercapacitors, flywheels, and compressed air energy storage**: Valuable for buffering and stationary applications, but bulk and low energy density make them unsuitable for portable emergency use.
- **E-fuels, ammonia, and LOHCs**: Long-term potential as fuels, but synthesis, logistics, and safety challenges preclude near-term PCP applicability.
- **Carnot batteries, tidal energy systems, and nuclear micro-reactors**: Either stationary, site-bound, or politically/regulatorily sensitive, and therefore unsuited for rapid deployment.
- **Pedal-powered generators**: Limited to micro-loads, not relevant for core operational requirements.

These technologies should be deprioritised for potential PCP preparation, though some may warrant long-term observation.

5.2.5. Commercial Off-the-Shelf (COTS) Summary

The fact sheets underline a tiered pattern of relevance. **COTS technologies** provide the strongest near-term candidates for potential PCP preparation, with lithium-ion, PEM fuel cells, photovoltaics, and hybrid gensets forming the likely core portfolio. **EHPETs** such as sodium-ion and solid-state batteries merit close monitoring, but their immaturity excludes them from immediate deployment. **EMHPETs** are promising on paper but remain confined to research and pilot projects, while **ELPETs** are largely misaligned with the operational profile of emergency response energy supply. This differentiation ensures that potential PCP efforts can focus resources on technologies most likely to deliver operational impact, while maintaining innovation pathways for the future.

5.3. Comparison and Added Value

The comparison of supplier survey results and the technology fact sheets highlights the value of combining bottom-up and top-down perspectives. Each strand of evidence provides insights that the other cannot deliver, and their integration allows for a more balanced understanding of the current state of the art.

The supplier survey offered a bottom-up snapshot of the market. It illustrated which providers are actively engaging with the identified requirements, how they position their products against operational needs, and to what degree they claim compliance. This makes it possible to identify a spectrum of self-declared readiness levels and to understand which requirement areas providers find easier or harder to address. At the same time, the survey results are heterogeneous, not independently validated, and in some cases refer to families of products or conceptual designs rather than deliverable systems.

The technology fact sheets, by contrast, provided a top-down analysis of entire technology classes. They allowed structural characteristics, trade-offs, and maturity levels to be mapped independently of individual supplier claims. For example, the fact sheets made clear why lithium-ion batteries and PEM fuel cells appear consistently in survey results with high compliance: both are mature COTS technologies that are already widely deployed. Conversely, they also explain why certain low compliance scores may not reflect unsuitability, but rather the immaturity or structural constraints of the underlying technology (e.g. flow batteries, biomass systems, or hydrogen storage concepts).

Taken together, the two strands are complementary. The survey identifies concrete suppliers and their self-reported coverage of requirements, while the fact sheets contextualise these claims by clarifying whether the underlying technology is structurally mature, emerging, or misaligned with rapid deployment needs. This combination prevents over-reliance on self-reported compliance, situates supplier claims within broader technological trajectories, and ensures that the PCP process can build on both market soundings and systematic technology analysis.

In this way, the integration of survey and fact sheet findings provides added value: it avoids premature endorsement of individual solutions, ensures that technology categories are evaluated on their structural merits, and prepares a robust basis for subsequent (potential PCP) steps that combine supplier engagement with targeted technical validation.

5.4. Implications for subsequent PCP steps

The combined evidence from the survey and the technology fact sheets provides an initial orientation for how a future PCP could be structured. Although neither dataset alone can serve as a definitive basis for selection, together they allow for a reasoned differentiation between technologies that appear more immediately suitable, those that may serve in complementary or niche roles, and those that should be monitored as part of longer-term innovation pathways.

COTS technologies emerge as the most promising candidates for near-term PCP activities. Lithium-ion batteries, portable PEM fuel cells, photovoltaic modules, and hybrid battery–genset systems demonstrate high maturity, modularity, and operational relevance. They also featured prominently in the survey results, where providers claimed broad compliance with the condensed requirement set. While each carries specific constraints, ranging from raw material supply to hydrogen logistics, these are manageable within a PCP framework. As such, these technologies can be considered strong candidates for early PCP lots or modules.

Context-specific and niche technologies, such as small wind and hydro, micro gas turbines, methanol systems, biomass and waste-to-energy, and flow batteries, show partial alignment with requirements. They may offer advantages in certain mission profiles (e.g. wind or hydro in favourable geographies, biomass for long-duration stationary bases, methanol for small-scale loads). However, their structural limitations mean that they are unlikely to serve as core PCP solutions without targeted adaptation. Their role is more likely to be complementary, providing redundancy or addressing specialised use cases.

Emerging technologies (EHPETs and EMHPETs), including sodium-ion, solid-state, lithium-sulphur, and perovskite photovoltaics, are not yet ready for inclusion in a near-term PCP. Their immaturity, unresolved technical barriers, or lack of COTS availability currently preclude operational deployment. Nonetheless, these technologies should remain on the innovation radar, either as part of PCP “innovation lots” or through dedicated R&D partnerships.

Low-priority technologies (ELPETs), such as supercapacitors, flywheels, CAES, LOHCs, ammonia, tidal systems, and nuclear micro-reactors, are structurally misaligned with rapid, portable deployment. Their role is limited to horizon scanning and long-term monitoring.

To consolidate this the comparison a tiering approach is provided as a pragmatic framework for designing the potential subsequent PCP phases. It allows the consortium to prioritise solutions most likely to deliver operational impact while maintaining awareness of promising innovations that could be integrated in future iterations.

5.4.1. Methodology of Tier Assignment

The tiering of technologies and products presented in this deliverable is based on a combined assessment of survey results and technology fact sheets. The approach follows three steps:

1. **Evidence base**: Fact sheets provided secondary data on technical performance, maturity, and operational aspects of 33 technologies. The supplier survey added self-reported compliance data for 24 market products. Both strands carry methodological limitations: survey responses reflect heterogeneous, self-declared inputs, while fact sheets rely on literature and often report performance ranges rather than definitive values.
2. **Benchmarking against requirements**: Technologies and products were qualitatively matched against the core functional and technical requirements identified in Deliverable 2.3 (e.g. transportability, modularity, scalability, safety, noise thresholds). Although a formal weighting of requirements will be

conducted in subsequent PCP steps, this analysis emphasised criteria of central operational importance.

3. **Indicative tiering**: Based on this comparison, technologies were grouped into four indicative tiers:

    - **Tier 1:** Commercially available (COTS) technologies or products that align well with the majority of requirements (e.g. lithium-ion batteries, PEM fuel cells, photovoltaic modules, hybrid battery–genset systems).
    - **Tier 2:** Solutions with conditional or niche suitability (e.g. small hydro, small wind, micro gas turbines, flow batteries).
    - **Tier 3:** Emerging promising technologies with high potential but current immaturity (e.g. sodium-ion, solid-state and lithium-sulphur batteries, perovskite photovoltaics).
    - **Tier 4:** Horizon technologies or products that are structurally misaligned with rapid-deployment needs (e.g. supercapacitors, compressed air storage, LOHCs, nuclear micro-reactors, and certain niche survey products such as very low-power DMFCs).

This classification should be read as indicative signals rather than validated evidence (a detailed list is provided in Annex 2). Its purpose is to support strategic orientation for PCP preparation by highlighting short-term candidates, context-specific options, and long-term innovation pipelines. Definitive validation will require subsequent PCP measures, including requirement weighting, clarification rounds with suppliers, and structured end-user testing.

5.4.2. Validation Needs and Next Steps

The differentiation of technologies into four tiers highlights not only which options are more immediately suitable for a potential PCP, but also where further validation is essential. At this stage, both the survey and the fact sheets provide indicative rather than validated evidence, and follow-up measures are required to establish a robust foundation for procurement.

For **Tier 1 (core COTS candidates)**, the priority is to verify self-reported compliance claims and to ensure product specificity. Survey entries occasionally referred to product families or conceptual descriptions rather than single, deliverable systems. Clarification rounds with providers are therefore needed to identify concrete product models, confirm compliance with minimum thresholds (e.g. continuous power, noise, safety), and obtain up-to-date datasheets and certifications. End-user testing in controlled conditions, such as mock deployments will be necessary to validate operational usability.

For **Tier 2 (context-specific or niche solutions)**, the emphasis should be on boundary testing and operational fit. Technologies such as micro gas turbines, biomass-based systems, or flow batteries may offer advantages in certain contexts but carry significant trade-offs. Validation should therefore explore under which conditions they become feasible, which requirements they fail to meet, and whether these gaps can realistically be addressed within a PCP framework.

For **Tier 3 (emerging technologies)**, the next step is not immediate validation for procurement, but structured monitoring. Pilot projects, R&D collaborations, or inclusion in innovation lots could provide opportunities to track progress and generate early operational insights. Technologies such as sodium-ion, solid-state, or perovskite PV may become viable within the timeframe of a PCP, but only if their performance and availability improve substantially.

For **Tier 4 (low-priority technologies)**, validation efforts should remain minimal. These options are primarily relevant for horizon scanning, and resources are better directed towards Tiers 1–3. Monitoring should remain limited to periodic technology assessments and literature reviews.

Across all tiers, three validation needs are consistent:

1. **Product specificity** – ensuring that candidate solutions are concrete and independently deployable.
2. **Requirement weighting** – introducing a preference matrix that distinguishes between core and secondary requirements, with “hard gates” for mandatory criteria.
3. **Operational verification** – involving end-users and technical experts in structured validation activities to ensure that solutions are realistically deployable under field conditions.

By following this tiered validation pathway, the consortium can move from a broad survey-based overview towards a refined set of technology options, ensuring that the subsequent PCP is based on robust, verified, and operationally relevant evidence.

6. Conclusion and Outlook

The combined evidence from the supplier survey and the technology fact sheets provides a structured and multi-layered picture of the current state of the art in sustainable, portable energy supply for emergency response. A total of **33 technologies** were analysed in detail, complemented by the identification of **20 integrated system solutions**. These 33 individual technologies were categorised into four sub-types:

- **12 Commercial Off-the-Shelf (COTS) technologies**, analysed through full fact sheets;
- **4 Emerging Highly Promising Technologies (EHPETs)**, also analysed through full fact sheets;
- **7 Emerging Moderately Promising Technologies (EMPETs)**, documented as concise mini-fact sheets; and
- **10 Emerging Lowly Promising Technologies (ELPETs)**, also summarised in mini-fact sheets.

This layered approach ensures that both currently deployable products and future-oriented technologies are covered in a consistent framework.

While each strand has methodological limitations – the **survey** especially due to its self-reported and heterogeneous inputs, and the **fact sheets** due to reliance on secondary data and performance ranges – their integration offers a robust starting point for a potential PCP preparation.

Four main insights can be drawn:

First, the market already offers a set of mature, commercial solutions (Tier 1) that align well with the requirements. Survey results confirm that lithium-ion batteries, portable PEM fuel cells, photovoltaic modules, and hybrid battery–genset systems are among the most promising technologies. They combine maturity, modularity, and partial validation through supplier responses. These are likely to form the backbone of an initial PCP portfolio. Nevertheless, most technologies and products address only one or two pillars (e.g. generation and conversion, or solely storage). Given that emergency response organisations are looking for integrated, holistic systems with certain properties (see D2.3), this structural gap must be considered and addressed in the next steps.

Second, while some holistic system solutions are already available on the market, they predominantly fall into two extremes: large container- or trailer-based systems that can exceed the required energy demand but are too heavy and bulky for rapid deployment (particularly via conventional aircraft), and small, highly portable devices that offer excellent mobility but provide only minimal capacity, insufficient to meet the electricity demand of emergency response organizations' bases of operations (BoO) and energy stations (ESs).

Third, several technologies demonstrate conditional or niche suitability (Tier 2). Small wind and hydro, micro gas turbines, biomass systems, flow batteries, and methanol-based solutions all exhibit advantages under specific conditions but are constrained by structural or operational limitations. These options may serve as complementary modules or redundancy measures rather than core PCP solutions.

Fourth, emerging technologies (Tiers 3 and 4) show high potential but remain either immature or structurally misaligned with the rapid deployment needs of emergency response. Sodium-ion, solid-state, lithium-sulfur, and perovskite photovoltaics warrant close monitoring and may be integrated through pilot activities or innovation lots. Others, such as supercapacitors, compressed air storage, ammonia, LOHCs, tidal energy, or nuclear micro-reactors, are better suited for horizon scanning at this stage.

Taken together, the evidence points towards a **tiered strategy**: prioritise **COTS solutions** as near-term candidates; selectively explore **context-specific technologies**; and monitor **emerging options** for future assessment iterations. Crucially, these insights must be complemented by further validation measures, including requirement weighting, clarification rounds with providers, and structured end-user testing.

The outlook for a potential PCP is therefore both **pragmatic and forward-looking**. Pragmatic, because the survey and fact sheets confirm that several technologies are already available and potentially deployable in modular ways. Forward-looking, because emerging technologies, though not yet ready, could shift the balance of feasibility in future procurement cycles. By keeping both dimensions in focus, the PCP process can deliver immediate operational impact while at the same time maintaining an innovation pipeline for the medium and long term.

7. References

1. Barry ES, Merkebu J, & Varpio L. State-of-the-art literature review methodology: A six-step approach for knowledge synthesis. *Perspect Med Educ* 2022; **11:** 281–8
2. ScienceDirect. Power Generation. https://www.sciencedirect.com/topics/engineering/power-generation (accessed 08/29/2025)
3. U.S. Energy Information Administration. Electricity explained How electricity is generated. https://www.eia.gov/energyexplained/electricity/how-electricity-is-generated.php (accessed 08/29/2025)
4. ScienceDirect. Energy Conversion. https://www.sciencedirect.com/topics/engineering/energy-conversion (accessed 08/29/2025)
5. Britannica. energy conversion. https://www.britannica.com/technology/energy-conversion (accessed 08/29/2025)
6. Baumeister T. Energy conversion. https://www.accessscience.com/content/article/a232700 (accessed 08/29/2025)
7. Solar Schools. Energy Conversion. https://solarschools.net/knowledge-bank/energy/conversion (accessed 08/29/2025)
8. IEA. *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach*, 2023
9. IEA. *Energy Technology Perspectives 2024*, 2024
10. IEA. *Renewables 2024*, 2024
11. COP28 IaG. *Tripling renewable power and doubling energy efficiency by 2030: Crucial steps towards 1.5°C*, 2023
12. IRENA. *World Energy Transitions Outlook 2023: 1.5°C Pathway*, 2023
13. IRENA. *Off-grid renewable energy statistics 2024*, 2024
14. Tsiropoulos I, Nijs W, Tarvydas D, Ruiz Castello P. *Towards net-zero emissions in the EU energy system by 2050*, 2020
15. Baum C. *Future Energy Storage Systems for Mobility Applications. Discussion Paper:* Fraunhofer-Gesellschaft, 2020
16. Thelen C, Nolte H, Kaiser M, *et al. Wege zu einem klimaneutralen Energiesystem: Bundesländer im Transformationsprozess“,*, 2024
17. Stephan A, Hettesheimer T, Neef C, *et al. Alternative Battery Technologies Roadmap 2030+:* Fraunhofer-Gesellschaft, 2023
18. Photovoltaics Report 2024 Fraunhofer ISE. https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html
19. Luque A, Hegedus S. *Handbook of Photovoltaic Science and Engineering:* Wiley, 2010
20. Maurya MR, Cabibihan J-J, Sadasivuni KK, Deshmukh K. A review on high performance photovoltaic cells and strategies for improving their efficiency. *Frontiers in Energy* 2022; **16:** 548–80
21. Nelson J. *The physics of solar cells.* London: Imperial College Press, 2003
22. Green MA, Dunlop ED, Yoshita M, *et al. Solar cell efficiency tables (Version 63):* Fraunhofer-Gesellschaft, 2024
23. Benghanem M, Haddad S, Alzahrani A, *et al.* Evaluation of the Performance of Polycrystalline and Monocrystalline PV Technologies in a Hot and Arid Region: An Experimental Analysis. *Sustainability* 2023; **15:** 14831
24. Malik AQ. Characterization of Photovoltaic (PV) Modules Under Real Operating Conditions. In: Sayigh A, ed. *Sustainable Energy Development and Innovation*. Innovative Renewable Energy. Cham: Springer International Publishing, 2022: 67–71
25. MET Group Countries. Solar panel size: choosing the right dimensions. https://group.met.com/en/mind-the-fyouture/mindthefyouture/solar-panel-size
26. Dambhare MV, Butey B, Moharil SV. Solar photovoltaic technology: A review of different types of solar cells and its future trends. *Journal of Physics: Conference Series* 2021; **1913:** 12053

27. IEA. World Energy Outlook 2020. https://www.iea.org/reports/world-energy-outlook-2020
28. Mordor Intelligence. Solar Photovoltaic (PV) Market Reports - Industry Solar Photovoltaic (PV) Market Reports - Industry Analysis, Size & Trends (2025 - 2030). https://www.mordorintelligence.com/industry-reports/solar-photovoltaic-market
29. Alpine PV competence. Air Transport Material Delivery. https://alpine-pv.ch/wiki/site-assessment/material-delivery-air-transport/
30. 8MSOLAR. Solar Energy in Disaster Relief, Portable Power and Crisis Response. https://8msolar.com/solar-energy-in-disaster-relief-portable-power-and-crisis-response/#:~:text=Disaster%20response%20teams%20need%20power,and%20coordination%20among%20rescue%20teams.
31. Hacke P, Lokanath S, Williams P, *et al.* A status review of photovoltaic power conversion equipment reliability, safety, and quality assurance protocols. *Renewable and Sustainable Energy Reviews* 2018; **82:** 1097–112
32. Okoroigwe FC, Okoroigwe EC, Ajayi OO, Agbo SN, Chukwuma JN. Photovoltaic Modules Waste Management: Ethical Issues for Developing Nations. *Energy Technology* 2020; **8**
33. Efaz ET, Rhaman MM, Imam SA, *et al.* A review of primary technologies of thin-film solar cells. *Engineering Research Express* 2021; **3:** 32001
34. Mohammad Bagher A. Types of Solar Cells and Application. *American Journal of Optics and Photonics* 2015; **3:** 94
35. Lee TD, Ebong A. Thin film solar technologies: a review. In: *2015 12th International Conference on High-capacity Optical Networks and Enabling/Emerging Technologies (HONET)*: IEEE, 2015: 1–10
36. Moon MMA, Rahman MF, Hossain J, Ismail ABM. Comparative Study of the Second Generation a-Si:H, CdTe, and CIGS Thin-Film Solar Cells. *Advanced Materials Research* 2019; **1154:** 102–11
37. Chopra KL, Paulson PD, Dutta V. Thin-film solar cells: an overview. *Progress in Photovoltaics: Research and Applications* 2004; **12:** 69–92
38. Zhang C, Zhang J, Ma X, Feng Q. Thin-Film Solar Cells Based on Amorphous Silicon. In: Zhang C, Zhang J, Ma X, Feng Q, eds. *Semiconductor Photovoltaic Cells*. Singapore: Springer Singapore, 2021: 177–238
39. Acevedo-Luna A, Bernal-Correa R, Montes-Monsalve J, Morales-Acevedo A. Design of thin film solar cells based on a unified simple analytical model. *Journal of Applied Research and Technology* 2017; **15:** 599–608
40. Muttumthala NL, Yadav A. A concise overview of thin film photovoltaics. *Materials Today: Proceedings* 2022; **64:** 1475–8
41. Zhang C, Zhang J, Ma X, Feng Q, eds. *Semiconductor Photovoltaic Cells.* Singapore: Springer Singapore, 2021
42. Maurya MR, Cabibihan J-J, Sadasivuni KK, Deshmukh K. A review on high performance photovoltaic cells and strategies for improving their efficiency. *Frontiers in Energy* 2022; **16:** 548–80
43. Sivaraj S, Rathanasamy R, Kaliyannan GV, *et al.* A Comprehensive Review on Current Performance, Challenges and Progress in Thin-Film Solar Cells. *Energies* 2022; **15:** 8688
44. Edoff M. Thin film solar cells: research in an industrial perspective. *Ambio* 2012; **41 Suppl 2:** 112–8
45. Fraunhofer ISE. Photovoltaics Report. https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/photovoltaics-report.html
46. Mordor Intelligence. Thin Film Solar PV Market Size & Share Analysis - Growth Trends & Forecasts (2025 - 2030)
47. Liu et al. 2019. World Small Hydropower Development Report 2019
48. Urošević BG, Marinović B. Ranking construction of small hydro power plants using multi-criteria decision analysis. *Renewable Energy* 2021; **172:** 1174–83

49. International Renewable Energy Agency. Renewable energy benefits: Leveraging local capacity for small-scale hydropower 2023
50. Karapici V, Trojer A, Lazarevikj M, *et al.* Opportunities of hidden hydropower technologies towards the energy transition. *Energy Reports* 2024; **12:** 5633–47
51. Nasir BA. Design Aspects of Small-Hydropower Plant. *Journal of Energy Research and Reviews* 2021: 1–9
52. Signe EBK, Tchatchouang LVN, Pokem P, Ekoube PA, Meva'a L, Nganhou J. Micro Hydro Power Plant for Sustainable Energy in Rural Electrification: A Case Study in Cameroon. *Journal of Power and Energy Engineering* 2023; **11:** 34–43
53. Knott J, Mueller M, Pander J, Geist J. Ecological assessment of the world's first shaft hydropower plant. *Renewable and Sustainable Energy Reviews* 2023; **187:** 113727
54. Klein S, Fox E. A review of small hydropower performance and cost. *Renewable and Sustainable Energy Reviews* 2022; **169:** 112898
55. Seme S, Sredenšek K, Praunseis Z, Štumberger B, Hadžiselimović M. Optimal price of electricity of solar power plants and small hydro power plants – Technical and economical part of investments. *Energy* 2018; **157:** 87–95
56. Manzano-Agugliaro F, Taher M, Zapata-Sierra A, Juaidi A, Montoya FG. An overview of research and energy evolution for small hydropower in Europe. *Renewable and Sustainable Energy Reviews* 2017; **75:** 476–89
57. Data Bridge Market Research. Global Small Hydropower Market Size, Share, and Trends Analysis Report – Industry Overview and Forecast to 2032. https://www.databridgemarketresearch.com/reports/global-small-hydropower-market
58. Coherent Market Insights. Small Hydropower Market Size and Trends - 2025-2032. https://www.coherentmarketinsights.com/industry-reports/small-hydropower-market
59. Grand View Research. Small Hydropower Market Size & Trends. https://www.grandviewresearch.com/industry-analysis/small-hydropower-market
60. Rosato A, Perrotta A, Maffei L. Commercial Small-Scale Horizontal and Vertical Wind Turbines: A Comprehensive Review of Geometry, Materials, Costs and Performance. *Energies* 2024; **17:** 3125
61. Naughton B, Houchens B, Summerville B, *et al.* Design Guidelines for Deployable Wind Turbines for Defense and Disaster Response Missions. *Journal of Physics: Conference Series* 2022; **2265:** 42074
62. Kassa BY, Baheta AT, Beyene A. Current Trends and Innovations in Enhancing the Aerodynamic Performance of Small-Scale, Horizontal Axis Wind Turbines: A Review. *ASME Open Journal of Engineering* 2024; **3**
63. Lauria A, Loprieno P, Francone A, Leone E, Tomasicchio GR. Recent advances in understanding the dynamic characterization of floating offshore wind turbines. *Ocean Engineering* 2024; **307:** 118189
64. Watson S, Moro A, Reis V, *et al.* Future emerging technologies in the wind power sector: A European perspective. *Renewable and Sustainable Energy Reviews* 2019; **113:** 109270
65. Shao W, Du X, Zhang W, Shi D, Zhang J, Tang P. Corrosion Mechanisms, Responses, and Mitigation Strategies for Steel Piles in Offshore Wind Turbines: A Comprehensive Review. *Materials and Corrosion* 2025
66. Muheisen AH, Yass MA, Irthiea IK. Enhancement of horizontal wind turbine blade performance using multiple airfoils sections and fences. *Journal of King Saud University - Engineering Sciences* 2023; **35:** 69–81
67. Anjanikumar, Bhavani J, Veeresham K, Pushpa Kumari J. Isolated Power Conditioning unit for Applications Involving Micro Wind Turbines. *E3S Web of Conferences* 2024; **540:** 3010
68. Mordor Intelligence. Small Wind Turbine Company List. https://www.mordorintelligence.com/industry-reports/small-wind-turbine-market/companies

69. Market Data Forecast. Global Small Wind Market Research Report. https://www.marketdataforecast.com/market-reports/small-wind-market
70. Bošnjaković M, Katinić M, Santa R, Marić D. Wind Turbine Technology Trends. *Applied Sciences* 2022; **12:** 8653
71. Aravindhan N, Bibin C, Ashok Kumar R*, et al.* Performance analysis of various types of ducted wind turbines – A review. *Materials Today: Proceedings* 2023; **80:** 188–94
72. Korthauer R. *Lithium-ion batteries: Basics and applications.* Berlin, Heidelberg: Springer, 2018
73. Bridgewater G, Capener MJ, Brandon J, Lain MJ, Copley M, Kendrick E. A Comparison of Lithium-Ion Cell Performance across Three Different Cell Formats. *Batteries* 2021; **7:** 38
74. Hettesheimer T, Neef C, Rosellón Inclán I*, et al. Lithium-Ion Battery Roadmap - Industrialization Perspectives toward 2030:* Fraunhofer-Gesellschaft, 2022
75. Warner J. *Lithium-Ion Battery Chemistries: A Primer.* Cambridge, MA: Elsevier, 2019
76. Just Lithium. About Lithium Voltage Range – All you need to know. https://justlithiumbattery.com/about-lithium-voltage-range-all-you-need-to-know/ (accessed 07/16/2025)
77. John-Joseph M, Gifford S. Faraday Insights - Issue 18: September 2023 Developments in Lithium-Ion Battery Cathodes. https://www.faraday.ac.uk/wp-content/uploads/2023/09/Faraday_Insights_18_FINAL.pdf (accessed 07/16/2025)
78. Carmargos P, dos Santos, Pedro H.J., Santos IR, Ribeiro GS. Perspectives on Li-ion battery categories for electric vehicle applications: A review of state of the art. https://www.researchgate.net/publication/360277206_Perspectives_on_Li-ion_battery_categories_for_electric_vehicle_applications_A_review_of_state_of_the_art (accessed 07/16/2025)
79. Wulandari T, Fawcett D, Majumder SB, Poinern E. Lithium-based batteries, history, current status, challenges, and future perspectives. https://www.researchgate.net/publication/374550024_Lithium-based_batteries_history_current_status_challenges_and_future_perspectives (accessed 07/16/2025)
80. Fu W, Wang Y, Kong K, Kim D, Wang F, Yushin G. Materials and Processing of Lithium-Ion Battery Cathodes. *Nanoenergy Advances* 2023; **3:** 138–54
81. Zhao Y, Behdad S. Electric Vehicle Battery Simulation: How Electrode Porosity and Thickness Impact Cost and Performance. In: *26th Design for Manufacturing and the Life Cycle Conference (DFMLC).* Proceedings of the ASME 2021 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC-CIE2021). volume 5. New York, NY, USA, Red Hook, NY: the American Society of Mechanical Engineers; Curran Associates Inc, 2021
82. Del Corso F, Mettlach H, Morcrette M*, et al.* HELIOS—High Energy Lithium Ion Storage Solutions: Comparative Assessment of 4 Chemistries of Cathode for EV and PHEV Applications. In: Briec E, Müller B, eds. *Electric Vehicle Batteries: Reports of the PPP European Green Vehicles Initiative*. Lecture Notes in Mobility Ser. Cham: Springer International Publishing, 2014: 1–17
83. Schommer A, Sciortino DD, Morrey D, Collier G. Experimental investigation of power available in lithium-ion batteries. *Journal of Power Sources* 2024; **618:** 235168
84. Giovanniello MA, Wu X-Y. Hybrid lithium-ion battery and hydrogen energy storage systems for a wind-supplied microgrid. *Applied Energy* 2023; **345:** 121311
85. Bowen T, Chernyakhovskiy I, Xu K, Gadzanku S, Coney K. USAID GRID-SCALE ENERGY STORAGE TECHNOLOGIES PRIMER. https://docs.nrel.gov/docs/fy21osti/76097.pdf (accessed 07/16/2025)
86. Quantmeyer F, Liu-Henke X. Modeling and identification of lithium-ion batteries for electric vehicles. In: Tomczuk BZ, ed. *2013 International Symposium on*

Electrodynamic and Mechatronic Systems (SELM 2013): Opole-Zawiercie, Poland, 15 - 18 May 2013. Piscataway, NJ: IEEE, 2013: 19–20
87. Samantaray Y, Cogswell DA, Cohen AE, Bazant MZ. Electrochemically-Resolved Acoustic Emissions Analysis for Li-Ion Battery Materials. *ECS Meeting Abstracts* 2024; **MA2024-02:** 481
88. Zhao Y, Pohl O, Bhatt AI, *et al.* A Review on Battery Market Trends, Second-Life Reuse, and Recycling. *Sustainable Chemistry* 2021; **2:** 167–205
89. Madani SS, Ziebert C, Marzband M. Thermal Characteristics and Safety Aspects of Lithium-Ion Batteries: An In-Depth Review. *Symmetry* 2023; **15:** 1925
90. Zhang X, Li Z, Luo L, Fan Y, Du Z. A review on thermal management of lithium-ion batteries for electric vehicles. *Energy* 2022; **238:** 121652
91. Wulandari T, Fawcett D, Majumder SB, Poinern GEJ. Lithium-based batteries, history, current status, challenges, and future perspectives. *Battery Energy* 2023; **2:** 20230030
92. Mordor Intelligence. Lithium-ion Battery Market Size & Share Analysis - Growth Trends & Forecasts (2025 - 2030). https://www.mordorintelligence.com/industry-reports/lithium-ion-battery-market (accessed 07/16/2025)
93. Vallera AM, Nunes PM, Brito MC. Why we need battery swapping technology. *Energy Policy* 2021; **157:** 112481
94. Altiparmak SO. China and Lithium Geopolitics in a Changing Global Market. *Chinese political science review* 2022: 1–20
95. Malpede M. The Dark Side of Batteries: Cobalt Mining and Children's Education in Sub-Saharan Africa. *International Economic Review* 2025
96. Giglio E. Extractivism and its socio-environmental impact in South America. Overview of the “lithium triangle”. 47-53 Paginazione / América Crítica, V. 5 N. 1 (2021) 2021
97. Burton J, Kemp D, Barnes R, Parmenter J. Mapping critical minerals projects and their intersection with Indigenous peoples' land rights in Australia. *Energy Research & Social Science* 2024; **113:** 103556
98. La Iglesia AH de, Alejano FL, Rivero AJL, La Iglesia DH de. Ethics of Planned Obsolescence in Lithium Batteries: Environmental and Social Implications. In: La Iglesia DH de, Paz Santana JF de, López Rivero AJ, eds. *New Trends in Disruptive Technologies, Tech Ethics and Artificial Intelligence*: *The DITTET 2023 Collection*, 1st edn. Advances in Intelligent Systems and Computing. Vol 1452. Cham: Springer Nature Switzerland; Imprint Springer, 2023: 271–79
99. Muthukumar P, Kumar A, Afzal M, *et al.* Review on large-scale hydrogen storage systems for better sustainability. *International Journal of Hydrogen Energy* 2023; **48:** 33223–59
100. Ma N, Zhao W, Wang W, Li X, Zhou H. Large scale of green hydrogen storage: Opportunities and challenges. *International Journal of Hydrogen Energy* 2024; **50:** 379–96
101. Panigrahi PK, Chandu B, Motapothula MR, Puvvada N. Potential Benefits, Challenges and Perspectives of Various Methods and Materials Used for Hydrogen Storage. *Energy & Fuels* 2024; **38:** 2630–53
102. Okonkwo PC, Barhoumi EM, Belgacem IB, *et al.* A focused review of the hydrogen storage tank embrittlement mechanism process,. *International Journal of Hydrogen Energy,* 2023; **48:** 12935–48
103. Yin L, Yang H, Ju Y. Review on the key technologies and future development of insulation structure for liquid hydrogen storage tanks. *International Journal of Hydrogen Energy* 2024; **57:** 1302–15
104. enargus. Wasserstoffverflüssigung. https://www.enargus.de/pub/bscw.cgi/d13721-2/*/*/Wasserstoffverfl%C3%BCssigung?op=Wiki.getwiki (accessed 02/07/2024)
105. Mekonnin AS, Wacławiak K, Humayun M, Zhang S, Ullah H. Hydrogen Storage Technology, and Its Challenges: A Review. *Catalysts* 2025; **15:** 260

106. JRC/EU. Hydrogen Storage: State-of-the-Art and Future (JRC report EUR 20995). https://publications.jrc.ec.europa.eu/repository/bitstream/JRC26493/EUR%2020995%20EN.pdf (accessed 07/25/2025)
107. Gardesten S, Modin J. Transportation of hydrogen A comprehensive analysis of the cost of different methods of transportation of hydrogen. https://www.diva-portal.org/smash/get/diva2%3A1780818/FULLTEXT01.pdf (accessed 07/25/2025)
108. Linde. Liquefied Hydrogen Tank Solutions. https://www.linde-engineering.com/products-and-services/plant-components/liquefied-hydrogen-tank-solutions (accessed 07/25/2025)
109. Naquash A, Agarwal N, Lee M. A Review on Liquid Hydrogen Storage: Current Status, Challenges and Future Directions. *Sustainability* 2024; **16:** 8270
110. Hydrogen Tools. Best Practices 2025
111. Credence Research. Type IV Hydrogen Storage Tank Market By Material Type (Carbon-Fiber Reinforced Polymer (CFRP), Glass-Fiber Reinforced Polymer (GFRP)); By Application (On-Board Vehicle Storage, Stationary Energy Storage, Portable Power Modules); By Pressure Rating (Up to 350 bar, 700 bar, Above 900 bar); By End-User (Automotive OEMs, Energy Utilities, Industrial Gas Suppliers, Defense & Aerospace); By Shape (Cylindrical, Spherical, Prismatic) – Growth, Share, Opportunities & Competitive Analysis, 2024 – 2032. https://www.credenceresearch.com/report/type-iv-hydrogen-storage-tank-market (accessed 07/25/2025)
112. Cryogenic Society of America. Return to the blog Launching a Groundbreaking Mobile Liquid Hydrogen System. https://www.cryogenicsociety.org/index.php?category=industry-news&id=158%3Alaunching-a-groundbreaking-mobile-liquid-hydrogen-system&option=com_dailyplanetblog&view=entry (accessed 07/25/2025)
113. Gul W, Xia YE, Gérard P, Ha SK. Characterization of Polymeric Composites for Hydrogen Tank. *Polymers* 2023; **15**
114. Beber VC, Abels G, Hesebeck O. Material Selection of Tanks for Storage and Transport of Liquid Organic Hydrogen Carriers: A Lightweight and Lifecycle Assessment Comparative Study of Metal, Polymer, and Composite Alternatives. *Energy Technology* 2025; **13**
115. Davies E, Ehrmann A, Schwenzfeier-Hellkamp E. Safety of Hydrogen Storage Technologies. *Processes* 2024; **12:** 2182
116. Global Market Insights Inc. Compressed Hydrogen Energy Storage Market Size - By Application, Analysis, Share, Growth Forecast, 2025 – 2034. https://www.gminsights.com/industry-analysis/compressed-hydrogen-energy-storage-market (accessed 02/12/2025)
117. Alekseev A. Leitprojekt TransHydDE: Wasserstoff-Verflüssigung, Speicherung, Transport und Anwendung von flüssigem Wasserstoff. https://www.wasserstoff-leitprojekte.de/lw_resource/datapool/systemfiles/elements/files/F4941D1CBA383928E0537E695E862E63/live/document/Wasserstoff-Verfl%C3%BCssigung%2C_Speicherung%2C_Transport_und_Anwendung_von_fl%C3%BCssigem_Wasserstoff__2_.pdf
118. Spherical Insights. Global Liquid Hydrogen Market Size, Share, and COVID-19 Impact Analysis, By Technology Type (Steam Methanreforming, Electrolysis), By Distribution Type (Pipelines, Cryogenic Tankers), By End-User Industry (Automotive, Transportation, Chemical & Petrochemical Analysis, Aerospace, Metallurgy, Heavy Industry, Others) und By Region (Nordamerika, Europa, Asien-Pazifik, Lateinamerika, Middle East. https://www.sphericalinsights.com/de/reports/liquid-hydrogen-market (accessed 02/10/2025)
119. Wolf M. AppLHy! – Transport and Application of Liquid Hydrogen: European Cryogenics Days, 28.03.2023.

https://indico.gsi.de/event/15856/contributions/69744/attachments/43302/60747/20230327-1700-mjw-PR%C3%84S_ECD-Hydrogen-AppLHy-Wolf.pdf (accessed 02/13/2025)
120. Reuß M, Dimos P, Léon A, Grube T, Robinius M, Stolten D. Hydrogen Road Transport Analysis in the Energy System: A Case Study for Germany through 2050. *Energies* 2021; **14:** 3166
121. Klopčič N, Grimmer I, Winkler F, Sartory M, Trattner A. A review on metal hydride materials for hydrogen storage. *Journal of Energy Storage* 2023; **72:** 108456
122. Moradi R, Groth KM. Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis. *International Journal of Hydrogen Energy* 2019; **44:** 12254–69
123. Chen R, Kim S, Chang Z. Redox Flow Batteries: Fundamentals and Applications. In: Khalid MAA, ed. *Redox - Principles and Advanced Applications*. Erscheinungsort nicht ermittelbar: IntechOpen, 2017
124. Zhang H, Li X, Zhang J. *Redox flow batteries*: *Fundamentals and applications.* Electrochemical energy storage and conversion. Boca Raton, London, New York: CRC Press Taylor & Francis Group, 2018
125. Weber AZ, Mench MM, Meyers JP, Ross PN, Gostick JT, Liu Q. Redox flow batteries: a review. *Journal of Applied Electrochemistry* 2011; **41:** 1137–64
126. Noack J, Roznyatovskaya N, Herr T, Fischer P. The Chemistry of Redox-Flow Batteries. *Angewandte Chemie (International ed. in English)* 2015; **54:** 9776–809
127. Olabi AG, Allam MA, Abdelkareem MA*, et al.* Redox Flow Batteries: Recent Development in Main Components, Emerging Technologies, Diagnostic Techniques, Large-Scale Applications, and Challenges and Barriers. *Batteries* 2023; **9:** 409
128. Soloveichik GL. Flow Batteries: Current Status and Trends. *Chemical reviews* 2015; **115:** 11533–58
129. Sánchez-Díez E, Ventosa E, Guarnieri M*, et al.* Redox flow batteries: Status and perspective towards sustainable stationary energy storage. *Journal of Power Sources* 2021; **481:** 228804
130. Poli N, Bonaldo C, Moretto M, Guarnieri M. Techno-economic assessment of future vanadium flow batteries based on real device/market parameters. *Applied Energy* 2024; **362:** 122954
131. Maksudovna Vafaeva K, Sanjeeva P. Comparative analysis of lithium-ion and flow batteries for advanced energy storage technologies. *MATEC Web of Conferences* 2024; **392:** 1176
132. Jumare IA. Energy storage with salt water battery: A preliminary design and economic assessment. *Journal of Energy Storage* 2019; **27:** 101130
133. Kamal Abdelrazek, Karim Mohsen, Ahmed Elsheikh. *Saltwater Battery Development:* Unpublished, 2023
134. Parmeshwarappa P, Gundlapalli R, Jayanti S. Power and Energy Rating Considerations in Integration of Flow Battery with Solar PV and Residential Load. *Batteries* 2021; **7:** 62
135. Scott A. Flow batteries, the forgotten energy storage device: They may soon emerge from the shadow of lithium ion to store renewable energy. *Chemical & Engineering News* 2023
136. Invinity Energy Systems. A Lifespan That Matches Your Renewable Assets. https://invinity.com/vanadium-flow-battery-lifespan (accessed 07/17/2025)
137. Ufine. How to Maintain and Extend the Life of Your Vanadium Redox Flow Battery? https://www.ufinebattery.com/blog/how-to-maintain-and-extend-the-life-of-your-vanadium-redox-flow-battery (accessed 07/17/2025)
138. EEPower. Vanadium-Flow Battery provides Containerized Multi-MegaWatt Solution. https://eepower.com/new-industry-products/vanadium-flow-battery-provides-containerized-multi-megawatt-solution (accessed 07/17/2025)
139. ITPO. Vanadium Flow Battery System for Energy Efficiency. https://itpo-tokyo.unido.org/en/technology_db/2984 (accessed 07/17/2025)

140. Colthorpe A. Sumitomo Electric deploys first vanadium flow battery for a community microgrid in Japan. https://www.energy-storage.news/sumitomo-electric-deploys-first-vanadium-flow-battery-for-a-community-microgrid-in-japan/ (accessed 07/17/2025)
141. Fischer A. Microgrid project using vanadium redox flow battery. https://pv-magazine-usa.com/2022/01/31/microgrid-project-using-vanadium-redox-flow-battery (accessed 07/17/2025)
142. Wikipedia. Vanadium redox battery. https://en.wikipedia.org/wiki/Vanadium_redox_battery (accessed 07/17/2025)
143. Blume N, Turek T, Minke C. Sustainability Development of Stationary Batteries: A Circular Economy Approach for Vanadium Flow Batteries. *Batteries* 2024; **10:** 240
144. Mordor Intelligence. Flow Battery Market Size - Industry Report on Share, Growth Trends & Forecasts Analysis (2025 - 2030) Source: https://www.mordorintelligence.com/industry-reports/flow-battery-market. https://www.mordorintelligence.com/industry-reports/flow-battery-market (accessed 07/17/2025)
145. Hazra SK, Kim MH, Meskher H*, et al.* Lithium-Free Redox Flow Batteries: Challenges and Future Prospective for Safe and Efficient Energy Storage. https://chemistry-europe.onlinelibrary.wiley.com/doi/10.1002/batt.202400100 (accessed 07/17/2025)
146. Mo S, Du L, Huang Z*, et al.* Recent Advances on PEM Fuel Cells: From Key Materials to Membrane Electrode Assembly. *Electrochemical Energy Reviews* 2023; **6**
147. Zhang Z, Liu X, Sui Z, Fan X, Song C. Research status analysis of proton exchange membrane fuel cell based on bibliometric method. *Ionics* 2024; **30:** 5929–49
148. SFC Energy AG. EFOY Pro. https://www.efoy-pro.com/ (accessed 01/27/2025)
149. Bosch. Das Bosch SOFC-Brennstoffzellensystem:. https://www.bosch-hydrogen-energy.com/de/sofc/ (accessed 01/27/2025)
150. Cigolotti V, Genovese M. *Tracking Market Trends - Stationry Fuel Cell Applications*: *IEA Technology Collaboration Programme - Advanced Fuel Cells*
151. Introspective Market Research. Fuel Cell Market by Type (PEMFC, SOFC, PAFC, MFC, DMFC, AFC), Application (Portable, Stationary, Vehicles (FCV)), Size (Small & Large), End User (Residential, Commercial & Industrial, Transportation, Data Centre, Military & Défense, Utility) and Region, Global Market Analysis and Forecast, 2024-2032. https://introspectivemarketresearch.com/reports/fuel-cell-market/ (accessed 01/16/2025)
152. Grand View Research. Fuel Cell Market Size, Share & Trends Analysis Report By Product (PEMFC, MCFC, PAFC, SOFC, AFC, MFC), By Components, By Fuel, By Size, By Application, By End-use, By Region, And Segment Forecasts, 2024 - 2030. https://www.grandviewresearch.com/industry-analysis/fuel-cell-market (accessed 01/16/2025)
153. Fraunhofer ISI. H2GO – Nationaler Aktionsplan Brennstoffzellen-Produktion. https://www.isi.fraunhofer.de/de/competence-center/neue-technologien/projekte/h2go.html (accessed 01/16/2025)
154. Deloitte, Ballard. Fueling the Future for Mobility: Hydrogen and fuel cell solutions for transportation. https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf (accessed 01/16/2025)
155. Global Market Insights Inc. Fuel Cell Market Size - By Product (PEMFC, DMFC, SOFC, PAFC & AFC, MCFC), By Application (Stationary, Portable, Transport), Regional Outlook & Global Forecast, 2024 – 2032. https://www.gminsights.com/industry-analysis/fuel-cell-market (accessed 01/16/2024)

156. FuelCellStore. Stationary Fuel Cell Power Applications. https://www.fuelcellstore.com/blog-section/fuel-cell-information/stationary-fuel-cell-power-applications (accessed 07/28/2025)
157. Zarabi Golkhatmi S, Asghar MI, Lund PD. A review on solid oxide fuel cell durability: Latest progress, mechanisms, and study tools. *Renewable and Sustainable Energy Reviews* 2022; **161:** 112339
158. Borup R, Meyers J, Pivovar B*, et al.* Scientific aspects of polymer electrolyte fuel cell durability and degradation. *Chemical reviews* 2007; **107:** 3904–51
159. Amaitik N, Zhang M, Xu Y, Clark T, Bastin L. Utilising Digital Twins for Smart Maintenance Planning of Fuel Cell in Electric Vehicles. *MATEC Web of Conferences* 2024; **401**
160. Yen-Hsiung Kiang. *Maintenance costs of Solid Oxide Fuel Cell (SOFC) module:* Unpublished, 2025
161. PowerUP. UP1K 1 kW portable hydrogen fuel cell based generator. https://powerup-tech.com/product/up1k (accessed 01/16/2025)
162. Bridge Energy Services. Microgrids, Fuel Cells, & Battery Energy Storage Systems. https://resilientconnecticut.uconn.edu/wp-content/uploads/sites/3830/2023/05/BES-CIRCA-Energy-Resilience-Mark-Sassi.pdf (accessed 07/28/2025)
163. Ma Z, Eichman J, Kurtz J. Fuel Cell Backup Power System for Grid Service and Micro-Grid in Telecommunication Applications. https://docs.nrel.gov/docs/fy18osti/70990.pdf (accessed 07/28/2025)
164. Rabbani RA. Dynamic Performance of a PEM Fuel Cell System. https://backend.orbit.dtu.dk/ws/portalfiles/portal/72795006/Dynamic_Performance_of_a_PEM_Fuel.pdf (accessed 07/28/2025)
165. Uekert T, Wikoff HM, Badgett A. Electrolyzer and Fuel Cell Recycling for a Circular Hydrogen Economy. *Advanced Sustainable Systems* 2024; **8**
166. Calabrese M, Portarapillo M, Di Nardo A*, et al.* Hydrogen Safety Challenges: A Comprehensive Review on Production, Storage, Transport, Utilization, and CFD-Based Consequence and Risk Assessment. *Energies* 2024; **17:** 1350
167. Straits Research. Fuel Cell Market Size, Share & Trends Analysis Report By Type (Proton Exchange Membrane Fuel Cell (PEMFC), Solid Oxide Fuel Cell (SOFC), Molten Carbonate Fuel Cell (MCFC), Direct Methanol Ful Cell (DMFC), Alkaline Fuel Cell (AFC), Others), By Fuel Type (Hydrogen, Methanol, Ammonia, Hydrocarbon, Others), By End-User (Aerospace, Energy & Power, Marine, Residential, Transportation, Others) and By Region(North America, Europe, APAC, Middle East and Africa, LATAM) Forecasts, 2025-2033. https://straitsresearch.com/report/fuel-cell-market/ (accessed 01/16/2025)
168. Accelera by Cummins. FCE150. https://www.accelerazero.com/fuel-cells/fce150 (accessed 01/27/2025)
169. Nedstack. Zero-Emission District Heat and Powe. https://nedstack.com/en (accessed 01/27/2025)
170. Zepp.solution. No emission. No problem. https://zepp.solutions/en/ (accessed 01/17/2025)
171. KBVresearch. Global Fuel Cell Market Size, Share & Industry Trends Analysis Report By Product Type, By Application (Stationary, Portable, and Transport), By Regional Outlook and Forecast, 2022 - 2028. https://www.kbvresearch.com/fuel-cell-market/?utm_source=chatgpt.com (accessed 07/28/2025)
172. SFC Energy AG. H_2Genset Der mobile emissionsfreie Generator. https://www.h2-genset.com/ (accessed 01/27/2025)
173. H2Sys. H2Sys Homepage. https://h2sys.fr/de/ (accessed 01/27/2025)
174. Skaggs K. ERDC-CERL to test new hydrogen electrolyzer technology to support energy resilience. https://www.erdc.usace.army.mil/Media/News-Stories/Article/3334362/erdc-cerl-to-test-new-hydrogen-electrolyzer-technology-to-support-energy-resili/ (accessed 01/17/2024)

175. Bonanno M, Müller K, Bensmann B, *et al.* Review and Prospects of PEM Water Electrolysis at Elevated Temperature Operation. *Advanced Materials Technologies* 2024; **9**
176. Kiemel S, Smolinka T, Lehner F, Full J, Sauer A, Miehe R. Critical materials for water electrolysers at the example of the energy transition in Germany. *International Journal of Energy Research* 2021; **45:** 9914–35
177. Dubouis N, Aymé-Perrot D, Degoulange D, Grimaud A, Girault H. Alkaline electrolyzers: Powering industries and overcoming fundamental challenges. *Joule* 2024; **8:** 883–98
178. Ren Z, Wang J, Yu Z, Zhang C, Gao S, Wang P. Experimental studies and modeling of a 250-kW alkaline water electrolyzer for hydrogen production. *Journal of Power Sources* 2022; **544:** 231886
179. Haoran C, Xia Y, Wei W, Yongzhi Z, Bo Z, Leiqi Z. Safety and efficiency problems of hydrogen production from alkaline water electrolyzers driven by renewable energy sources. *International Journal of Hydrogen Energy* 2024; **54:** 700–12
180. Du N, Roy C, Peach R, Turnbull M, Thiele S, Bock C. Anion-Exchange Membrane Water Electrolyzers. *Chemical reviews* 2022; **122:** 11830–95
181. Li D, Motz AR, Bae C, *et al.* Durability of anion exchange membrane water electrolyzers. *Energy & Environmental Science* 2021; **14:** 3393–419
182. Hauch A, Küngas R, Blennow P, *et al.* Recent advances in solid oxide cell technology for electrolysis. *Science (New York, N.Y.)* 2020; **370**
183. Flis G, Wakim G. Solid Oxide Electrolysis: A Technology Status Assessment. https://cdn.catf.us/wp-content/uploads/2023/11/15092028/solid-oxide-electrolysis-report.pdf (accessed 01/28/2025)
184. nel. PEM Electrolyser – MC Series. https://nelhydrogen.com/product/mc-series-electrolyser/ (accessed 02/03/2025)
185. Quest One. PEM-Elektrolyseur ME450. https://www.questone.com/produkte/detail/quest-one-pem-elektrolyseur-me450/me450/ (accessed 07/14/2025)
186. US Department of Energy. Technical Targets for Proton Exchange Membrane Electrolysis. https://www.energy.gov/eere/fuelcells/technical-targets-proton-exchange-membrane-electrolysis (accessed 07/14/2025)
187. CSIRO Energy. Cost assessment of hydrogen production from PV and electrolysis. https://arena.gov.au/assets/2016/05/Assessment-of-the-cost-of-hydrogen-from-PV.pdf (accessed 07/14/2025)
188. AZO materials. Containerized PEM Hydrogen Generators: 246 to 492 Nm^3/h. https://www.azom.com/equipment-details.aspx?EquipID=7494 (accessed 07/14/2025)
189. Hydrogen Training Solutions. Principles of PEM Electrolyser Operation Training Course. https://www.hydrogentrainingsolutions.co.uk/principles-of-pem-electrolyser-operation (accessed 07/14/2025)
190. Ahaotu MC, Ogbogu CE, Thornburg J, Akwukwaegbu IO. Simulation of PEM Electrolyzer Power Management with Renewable Generation in Owerri, Nigeria. *Energies* 2025; **18:** 208
191. Sany Hydrogen Energy. What is the noise level of Pem Water Electrolyser during operation? https://www.sanyhydrogenenergy.com/blog/what-is-the-noise-level-of-pem-water-electrolyser-during-operation-478676.html (accessed 07/14/2025)
192. Kylin-tech. PEM Small and Medium PEM Electrolysis Equipment 2-10NM3/Hour. https://en.kylin-tech.com/product/28.html (accessed 07/14/2025)
193. RSK Acoustics. Whitelee Planning Support - Noise Assessment. https://www.scottishpowerrenewables.com/userfiles/file/Whitelee_Planning_Support.pdf (accessed 07/14/2025)
194. Heraeus. Recycling of Critical Raw Materials for a Circular Hydrogen Economy. https://www.heraeus-precious-metals.com/en/products-solutions-by-

category/hydrogen-systems/recycling-solutions-for-a-circular-hydrogen-economy (accessed 07/14/2025)
195. Hotellier G, Becker I. SAFETY CONCEPT OF A SELF-SUSTAINING PEM HYDROGEN ELECTROLYZER SYSTEM. https://h2tools.org/sites/default/files/2019-08/paper_193.pdf (accessed 05/14/2025)
196. Murphy D. Hydrogen Safety for Large-Scale Electrolyzer Installations. https://www.energy.gov/sites/default/files/2023-11/2-02-safety-murphy.pdf (accessed 07/14/2025)
197. FuelCellStore. SGH2 2kW Alkaline Water Electrolysis Stack. https://www.fuelcellstore.com/sgh2-2kw-alkaline-water-electrolysis-stack (accessed 07/14/2025)
198. PERIC. Integrated-type H2 Generator. https://www.peric718.com/Alkaline-Type-Hydrogen-G/r-86.html (accessed 07/14/2025)
199. McPhy. MCLYZER PRODUCT LINE -Pressurized alkaline electrolysis. https://cellar-c2.services.clever-cloud.com/com-mcphy/uploads/2023/06/2023_McLyzer-Product-Line-EN.pdf (accessed 07/14/2025)
200. Groot TT de. (Invited) Challenges and Opportunities of Alkaline Water Electrolysis. *ECS Meeting Abstracts* 2023; **MA2023-01:** 1972
201. Kim M, Lee C, Lee S, Doo G, Seo J, Cho H-S. (Invited) Improvement in Dynamic Operational Stability of Alkaline Water Electrolysis. *ECS Meeting Abstracts* 2024; **MA2024-02:** 3504
202. Mitsushima S, Hino S, Nagasawa K*, et al.* (Invited) Reverse Current Behavior and ADT Protocol for Start & Stop Operation of Bipolar Alkaline Water Electrolyzer. *ECS Meeting Abstracts* 2020; **MA2020-01:** 1835
203. Brauns J, Turek T. Alkaline Water Electrolysis Powered by Renewable Energy: A Review. *Processes* 2020; **8:** 248
204. Munther H, Hassan Q, Khadom AA, Mahood HB. Evaluating the techno-economic potential of large-scale green hydrogen production via solar, wind, and hybrid energy systems utilizing PEM and alkaline electrolyzers. *Unconventional Resources* 2025; **5:** 100122
205. Enapter. Mobile Nanogrid for disaster response. https://www.enapter.com/application/mobile-nanogrid-for-disaster-response (accessed 01/17/2025)
206. Abdelhaleem A, Kuroda Y, Kawakami N, Souda M, Mitsushima S. Exploring the Performance of Alkaline Water Electrolyzers Under Dynamic Operational Conditions. *ECS Meeting Abstracts* 2024; **MA2024-01:** 1820
207. Diéguez PM, Ursúa A, Sanchis P, Sopena C, Guelbenzu E, Gandía LM. Thermal performance of a commercial alkaline water electrolyzer: Experimental study and mathematical modeling. *International Journal of Hydrogen Energy* 2008; **33:** 7338–54
208. Zhao Z, Yuan H, Tian Y, Zhang H. A novel method for rotor profile optimization of high temperature screw expanders employed in waste heat recovery systems. *International Journal of Energy Research* 2021; **45:** 8551–63
209. Shiva Kumar S, Himabindu V. Hydrogen production by PEM water electrolysis – A review. *Materials Science for Energy Technologies* 2019; **2:** 442–54
210. Enapter. AEM Elektrolyseure - das Beste aus zwei Welten. https://www.enapter.com/de/aem-electrolysers/ (accessed 02/03/2025)
211. Yang Y, Li P, Zheng X*, et al.* Anion-exchange membrane water electrolyzers and fuel cells. *Chemical Society reviews* 2022; **51:** 9620–93
212. Moreno-González M, Mardle P, Zhu S*, et al.* One year operation of an anion exchange membrane water electrolyzer utilizing Aemion+® membrane: Minimal degradation, low H2 crossover and high efficiency. *Journal of Power Sources Advances* 2023; **19:** 100109
213. Liu F, Miyatake K, Tanabe M*, et al.* High-Performance Anion Exchange Membrane Water Electrolyzers Enabled by Highly Gas Permeable and

Dimensionally Stable Anion Exchange Ionomers. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)* 2024; **11:** e2402969
214. Zhang X, Li Y, Zhao W, Guo J, Yin P, Ling T. Technical factors affecting the performance of anion exchange membrane water electrolyzer. *International Journal of Minerals, Metallurgy and Materials* 2023; **30:** 2259–69
215. Enapter. AEM Electrolyzer EL 4. https://www.enapter.com/en/product/aem-electrolyzer-el-4 (accessed 07/14/2025)
216. Hydrogen Energy. Hygreen Energy Launches New AEM Electrolyzer Systems, Delivery Begins September 2024. https://www.hygreenenergy.com/hygreen-energy-launches-new-aem-electrolyzer-systems (accessed 07/15/2025)
217. Enapter. Education is the key to scaling green hydrogen! https://www.instagram.com/enapter/p/DDcbVb9oO1j (accessed 07/15/2025)
218. Enapter. Electricity Storage. https://www.enapter.com/en/aem-by-enapter/fields-of-application/electricity-storage (accessed 07/15/2025)
219. Enapter. EL 2.1 Hydrogen Generator (35bar) Owner's Manual. https://handbook.enapter.com/electrolyser/el21/downloads/ELE21-MAN-00001_REV05.pdf (accessed 05/15/2025)
220. ansaldo green tech. AEM ELECTROLYSER. https://www.ansaldoenergia.com/fileadmin/2025/Electrolyser/AEM_electrolyser.pdf (accessed 05/15/2025)
221. Enapter. Enapter AG publishes first ESG report following ESRS standards. https://www.enapter.com/en/press-release/enapter-publishes-esg-report-2023 (accessed 07/15/2025)
222. Enapter. Software, Control, Safety and Certification. https://handbook.enapter.com/knowledge_base/software_control_safety_certification.html (accessed 07/15/2025)
223. Enapter. FAQs. https://www.enapter.com/en/aem-by-enapter/faqs (accessed 07/15/2025)
224. Ghezel-Ayagh H. Solid Oxide Electrolysis System Demonstration: DOE Hydrogen Program, 2023 Annual Merit Review and Peer Evaluation Meeting. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/ta039_ghezel-ayagh_2023_o-pdf.pdf (accessed 07/15/2025)
225. Sunfire. Sunfire-HyLink SOEC. https://backend.sunfire.de/wp-content/uploads/2024/10/Sunfire_Fact-Sheet_SOEC_EN_digital.pdf?utm_source=chatgpt.com (accessed 07/15/2025)
226. Sun X, Hendriksen PV, Mogensen MB, Chen M. Degradation in Solid Oxide Electrolysis Cells During Long Term Testing. https://backend.orbit.dtu.dk/ws/portalfiles/portal/222412215/_system_appendPDF_proof_hi_new.pdf (accessed 07/15/2025)
227. Institute for Sustainable Process Technolgy. Next Level Solid Oxide Electrolysis. https://ispt.eu/media/20230508-FINAL-SOE-public-report-ISPT.pdf (accessed 07/15/2025)
228. Topsoe. High Performance Electrolyse. https://www.topsoe.com/soec (accessed 02/03/2025)
229. POLITECNICO DI TORINO. Solid Oxide Electrolysis System: Dynamic modelling and microgrid integration. https://webthesis.biblio.polito.it/7385/1/tesi.pdf (accessed 07/15/2025)
230. Völs P, Veiga Barreiros T, Laplana AD, Sandig-Predzymirska L, Charitos A. Leaching of Solid Oxide Electrolyzer Cells for a Circular Hydrogen Economy. *Journal of Sustainable Metallurgy* 2025; **11:** 1766–77
231. Dragan M. Closing the Loop: Solid Oxide Fuel and Electrolysis Cells Materials for a Net-Zero Economy. *Materials (Basel, Switzerland)* 2024; **17**
232. Wolf SE, Winterhalder FE, Vibhu V, *et al.* Solid oxide electrolysis cells – current material development and industrial application. *Journal of Materials Chemistry A* 2023; **11:** 17977–8028

233. Chou Y-S, Hardy J, Marina OA. eak test for solid oxide fuel cells and solid oxide electrolysis cells. *Front. Energy Res.* 2022; **10:** 945788
234. Precedence Research. PEM Water Electrolyzer Market Size, Share, and Trends 2024 to 2034. https://www.precedenceresearch.com/pem-water-electrolyzer-market (accessed 01/28/2025)
235. Fortune Business insights. Alkaline Water Electrolysis Market Size, Share & Industry Analysis, By Type (10 m3/h, 30 m3/h, 50 m3/h, 80 m3/h, and 80 m3/h), By Application (Power Plants, Steel Plant, Electronics and Photovoltaics, Industrial Gases, and Others), and Regional Forecast, 2024-2032. https://www.fortunebusinessinsights.com/alkaline-water-electrolysis-market-105436 (accessed 02/03/2025)
236. Verified Market Reports. Global AEM Electrolyser Market By Type (0.5Nm3/h, 1Nm3/h), By Application (Hydrogen Refueling Station, Seasonal Energy Storage), By Geographic Scope And Forecast. https://www.verifiedmarketreports.com/product/aem-electrolyser-market/ (accessed 02/03/2025)
237. Knowledge Sourcing Intelligence. SOEC Electrolyzer Market Size, Share, Opportunities, And Trends By Component (BOP, Stack), By Application (Hydrogen Production, Industrial Process, Others), By End-User (Power, Transportation, Refineries, Others), And By Geography - Forecasts From 2025 To 2030. https://www.knowledge-sourcing.com/report/soec-electrolyzer-market (accessed 02/03/2025)
238. nel. Water electrolysers / hydrogen generators. https://nelhydrogen.com/water-electrolysers-hydrogen-generators/ (accessed 01/28/2025)
239. Siemens. Green hydrogen production. https://www.siemens-energy.com/global/en/home/products-services/product-offerings/hydrogen-solutions.html (accessed 01/29/2025)
240. Plug Power. Best-in-Class Electrolyzer Products Plug's electrolyzer products are m. https://www.plugpower.com/hydrogen/electrolyzer-hydrogen/electrolyzer-products/ (accessed 02/03/2025)
241. Prophecy Market Insights. Pem Electrolyzer Market Companies. https://www.prophecymarketinsights.com/de/market_insight/pem-electrolyzer-market-5867/market-companies (accessed 07/15/2025)
242. Tüysüz H. Alkaline Water Electrolysis for Green Hydrogen Production. *Accounts of chemical research* 2024; **57:** 558–67
243. Enapter. Applications. https://www.enapter.com/en/application/mobile-nanogrid-for-disaster-response/ (accessed 07/15/2025)
244. US Department of Energy. Hydrogen Production: Electrolysis. https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis (accessed 01/27/2025)
245. Banihabib R, Assadi M. The Role of Micro Gas Turbines in Energy Transition. *Energies* 2022; **15:** 8084
246. Wołowicz M, Kolasiński P, Badyda K. Modern Small and Microcogeneration Systems—A Review. *Energies* 2021; **14:** 785
247. Samitha Weerakoon AH, Assadi M. Trends and advances in micro gas turbine technology for sustainable energy solutions: A detailed review. *Energy Conversion and Management: X* 2023; **20:** 100483
248. Alhuyi Nazari M, Fahim Alavi M, Salem M, Assad MEH. Utilization of hydrogen in gas turbines: a comprehensive review. *International Journal of Low-Carbon Technologies* 2022; **17:** 513–9
249. Escamilla A, Sánchez D, García-Rodríguez L. Assessment of power-to-power renewable energy storage based on the smart integration of hydrogen and micro gas turbine technologies. *International Journal of Hydrogen Energy* 2022; **47:** 17505–25
250. Li J, Li Y. Micro gas turbine: Developments, applications, and key technologies on components. *Propulsion and Power Research* 2023; **12:** 1–43

251. Balli O, Ekici S, Karakoc HT. Achieving a more efficient and greener combined heat and power system driven by a micro gas turbine engine: Issues, opportunities, and benefits in the presence of thermodynamic perspective. *International Journal of Energy Research* 2021; **45:** 8620–38
252. Baqir Hashmi M, Mansouri M, Assadi M. Dynamic performance and control strategies of micro gas turbines: State-of-the-art review, methods, and technologies. *Energy Conversion and Management: X* 2023; **18:** 100376
253. Montazerinejad H, Eicker U. Recent development of heat and power generation using renewable fuels: A comprehensive review. *Renewable and Sustainable Energy Reviews* 2022; **165:** 112578
254. Robbio R de. Micro Gas Turbine Role in Distributed Generation with Renewable Energy Sources. *Energies* 2023; **16:** 704
255. Bonasio V, Ravelli S. Performance Analysis of an Ammonia-Fueled Micro Gas Turbine. *Energies* 2022; **15:** 3874
256. Aslanidou I, Rahman M, Zaccaria V, Kyprianidis KG. Micro Gas Turbines in the Future Smart Energy System: Fleet Monitoring, Diagnostics, and System Level Requirements. *Frontiers in Mechanical Engineering* 2021; **7**
257. Global Market Insights. Micro Gas Turbine Market Size, Industry Analysis and Forecast. https://www.gminsights.com/industry-analysis/micro-gas-turbine-market
258. Fortune Business insights. Microturbine Market Size, Share and COVID-19 Impact Analysis. https://www.fortunebusinessinsights.com/industry-reports/microturbine-market-100514
259. Acute Market Reports. Microturbines Market – Growth, Future Prospects, and Competitive Analysis. https://www.acutemarketreports.com/report/microturbines-market
260. Zhang Q, Banihabib R, Fadnes FS, Sazon TAS, Ahmed N, Assadi M. Techno-economic analysis of a biogas-fueled micro gas turbine cogeneration system with seasonal thermal energy storage. *Energy Conversion and Management* 2023; **292:** 117407
261. Abouemara K, Shahbaz M, Mckay G, Al-Ansari T. The review of power generation from integrated biomass gasification and solid oxide fuel cells: current status and future directions. *Fuel* 2024; **360:** 130511
262. Situmorang YA, Zhao Z, Yoshida A, Abudula A, Guan G. Small-scale biomass gasification systems for power generation (<200 kW class): A review. *Renewable and Sustainable Energy Reviews* 2020; **117:** 109486
263. Porcu A, Sollai S, Marotto D, Mureddu M, Ferrara F, Pettinau A. Techno-Economic Analysis of a Small-Scale Biomass-to-Energy BFB Gasification-Based System. *Energies* 2019; **12:** 494
264. Costa M, Piazzullo D, Di Battista D, Vita A de. Sustainability assessment of the whole biomass-to-energy chain of a combined heat and power plant based on biomass gasification: biomass supply chain management and life cycle assessment. *Journal of environmental management* 2022; **317:** 115434
265. Banerjee N. Biomass to Energy — an Analysis of Current Technologies, Prospects, and Challenges. *BioEnergy Research* 2023; **16:** 683–716
266. Gnanasekaran L, Priya AK, Thanigaivel S, Hoang TK, Soto-Moscoso M. The conversion of biomass to fuels via cutting-edge technologies: Explorations from natural utilization systems. *Fuel* 2023; **331:** 125668
267. Sharma S, Mallikarjuna Reddy V, Raj R G*, et al.* Leveraging Waste-to-Energy Technologies for Sustainable Development: A Comprehensive Review. *E3S Web of Conferences* 2024; **529:** 2010
268. Monteiro E, Ferreira S. Biomass Waste for Energy Production. *Energies* 2022; **15:** 5943
269. Hamrang F, Shokri A, Mahmoudi SMS, Ehghaghi B, Rosen MA. Performance Analysis of a New Electricity and Freshwater Production System Based on an Integrated Gasification Combined Cycle and Multi-Effect Desalination. *Sustainability* 2020; **12:** 7996

270. Chou C-J, Jiang S-B, Yeh T-L, Tsai L-D, Kang K-Y, Liu C-J. [Duplikat] A Portable Direct Methanol Fuel Cell Power Station for Long-Term Internet of Things Applications. *Energies* 2020; **13:** 3547
271. Moreira CS, Pinto AMFR, Oliveira VB. [Duplikat] The Effect of a Reduction in the Catalyst Loading on a Mini Passive Direct Methanol Fuel Cell. *Energies* 2024; **17:** 5174
272. Papavasiliou J, Schütt C, Kolb G, Neophytides S, Avgouropoulos G. Technological aspects of an auxiliary power unit with internal reforming methanol fuel cell. *International Journal of Hydrogen Energy* 2019; **44:** 12818–28
273. Jayakumar A, Madheswaran DK, Kumar NM. [Duplikat] A Critical Assessment on Functional Attributes and Degradation Mechanism of Membrane Electrode Assembly Components in Direct Methanol Fuel Cells. *Sustainability* 2021; **13:** 13938
274. Alias MS, Kamarudin SK, Zainoodin AM, Masdar MS. [Duplikat] Active direct methanol fuel cell: An overview. *International Journal of Hydrogen Energy* 2020; **45:** 19620–41
275. Sun S, Zhao M, Wang Q*, et al.* [Duplikat] Flexible All-Solid-State Direct Methanol Fuel Cells with High Specific Power Density. *Small (Weinheim an der Bergstrasse, Germany)* 2023; **19:** e2205835
276. Mordor Intelligence. Direct Methanol Fuel Cells Market Source. https://www.mordorintelligence.com/industry-reports/global-direct-methanol-fuel-cells-market-industry
277. Farrok O, Ahmed K, Tahlil AD, Farah MM, Kiran MR, Islam MR. Electrical Power Generation from the Oceanic Wave for Sustainable Advancement in Renewable Energy Technologies. *Sustainability* 2020; **12:** 2178
278. Wikipedia. Wave Power. https://en.wikipedia.org/wiki/Wave_power (accessed 09/15/2025)
279. Ambühl S, Marquis L, Kofoed JP, Dalsgaard Sørensen J. Operation and maintenance strategies for wave energy converters. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability* 2015; **229:** 417–41
280. Buscaino G, Mattiazzo G, Sannino G*, et al.* Acoustic impact of a wave energy converter in Mediterranean shallow waters. *Scientific reports* 2019; **9:** 9586
281. Thomas N, Dr. Senthil Prakash M. N. WAVE ENERGY CONVERTERS : COMPARISON & DESIGN ASPECTS. https://www.irjmets.com/uploadedfiles/paper/volume2/issue_11_november_2020/4729/1628083189.pdf (accessed 09/15/2025)
282. Linquip Technews. Wave Energy Advantages and Disadvantages (2023 Update). https://www.linquip.com/blog/wave-energy-advantages-disadvantages/ (accessed 09/15/2025)
283. MarketsandMarkets. Wave Energy Market – Global Forecast 2027. https://www.marketsandmarkets.com/Market-Reports/wave-energy-market-217091216.html (accessed 09/15/2025)
284. NREL. Designing the Future of Wave Energy. https://www.nrel.gov/news/detail/program/2023/designing-the-future-of-wave-energy (accessed 09/15/2025)
285. Li H, Shi X, Kong W*, et al.* Advanced wave energy conversion technologies for sustainable and smart sea: A comprehensive review. *Renewable Energy* 2025; **238:** 121980
286. IMPACT H2020. Wave Energy Converters: What fails and why? https://www.impact-h2020.eu/2022/03/28/wave-energy-converters-what-fails-and-why/ (accessed 09/15/2025)
287. Climate Insider. Top Wave Energy Companies. https://climateinsider.com/2024/10/01/wave-energy-companies/ (accessed 09/15/2025)

288. Solar Reviews. Wave Energy: Pros and Cons. https://www.solarreviews.com/blog/wave-energy-pros-and-cons (accessed 09/15/2025)
289. Earth.org. The Pros and Cons of Wave Energy. https://earth.org/the-pros-and-cons-of-wave-energy/ (accessed 09/15/2025)
290. IRENA. Wave Energy: Technology Brief. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/Wave-Energy_V4_web.pdf (accessed 09/15/2025)
291. CICEnergyGune. Achievements and challenges of sodium-ion battery materials,. https://cicenergigune.com/en/blog/achievements-challenges-sodium-ion-battery-materials (accessed 09/15/2025)
292. Hwang J-Y, Myung S-T, Sun Y-K. Sodium-ion batteries: present and future. *Chemical Society reviews* 2017; **46:** 3529–614
293. Nayak PK, Yang L, Brehm W, Adelhelm P. From Lithium-Ion to Sodium-Ion Batteries: Advantages, Challenges, and Surprises. *Angewandte Chemie (International ed. in English)* 2018; **57:** 102–20
294. Faradion. Strong Performance. https://faradion.co.uk/technology-benefits/strong-performance/ (accessed 09/15/2025)
295. CNEVpost. World's first GWh-class sodium-ion battery production line sees first product off line. https://cnevpost.com/2022/12/02/hina-gwh-sodium-ion-battery-production-line-first-product/ (accessed 09/15/2025)
296. Hinabattery. Homepage. https://www.hinabattery.com/index.php?catid=28 (accessed 09/15/2025)
297. European Association for Storage of Energy. Sodium-Ion Battery. https://ease-storage.eu/wp-content/uploads/2016/07/EASE_TD_Electrochemical_NaIon.pdf (accessed 09/15/2025)
298. North America, Europe, South America, Asia Pacific, Middle East and Africa (Factor (Prismatic, Cylindrical, Pouch) and By Regional) Jaiswal, C. Sodium-Ion Battery Market Research Report By Application (Electric Vehicles, Energy Storage Systems, Consumer Electronics, Industrial Applications), By Chemistry Type (Sodium Nickel Manganese Chloride, Sodium Sulfur, Sodium Iron Phosphate), By End Use (Automotive, Residential, Commercial, Utility), By Form - Forecast to 2035, Market Research Future. https://www.marketresearchfuture.com/reports/sodium-ion-battery-market-19273 (accessed 09/15/2025)
299. ArenaEV. JAC Group delivers first EVs with sodium-ion. https://www.arenaev.com/jac_group_delivers_first_evs_with_sodiumion_battery-news-2967.php (accessed 09/15/2025)
300. Liu J, Sun L, Yang J*, et al.* Ti-Mn hydrogen storage alloys: from properties to applications. *RSC advances* 2022; **12:** 35744–55
301. Egeland-Eriksen T, Hajizadeh A, Sartori S. Hydrogen-based systems for integration of renewable energy in power systems: Achievements and perspectives. *International Journal of Hydrogen Energy* 2021; **46:** 31963–83
302. Introspective Market Research. Hydrogen Storage Market Projected to Reach USD 8.06 Billion by 2032, Growing at a CAGR of 21%. https://www.globenewswire.com/news-release/2024/12/16/2997544/0/en/Hydrogen-Storage-Market-Projected-to-Reach-USD-8-06-Billion-by-2032-Growing-at-a-CAGR-of-21-Introspective-Market-Research.html (accessed 09/15/2025)
303. Lototskyy MV, Tolj I, Davids MW*, et al.* Metal hydride hydrogen storage and supply systems for electric forklift with low-temperature proton exchange membrane fuel cell power module,. *International Journal of Hydrogen Energy,* 2016; **41:** 13831-13842,
304. Sheffield JW, Martin KB, Folkson R. Electricity and hydrogen as energy vectors for transportation vehicles. In: Folkson R, ed. *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance*: *Towards Zero Carbon*

Transportation. Woodhead Publishing Series in Energy. Vol 57. Amsterdam: Woodhead Publ, 2014: 117–37
305. Qayyum F, Umar M, Dölling J, Guk S, Prahl U. Mechanics of New-Generation Metals and Alloys. In: Silberschmidt VV, ed. *Comprehensive mechanics of materials*. Amsterdam: Elsevier, 2024: 31–57
306. Wu D, Chen L, Li H, Wu F. Solid-state lithium batteries-from fundamental research to industrial progress. *Progress in Materials Science* 2023; **139:** 101182
307. Aizat Razali A, Norazli SN, Sum WS, Yeo SY, Dolfi A, Srinivasan G. State-of-the-Art of Solid-State Electrolytes on the Road Map of Solid-State Lithium Metal Batteries for E-Mobility. *ACS Sustainable Chemistry & Engineering* 2023; **11:** 7927–64
308. Yavuz NK. Solid-State Batteries: Fundamentals and Challenges. In: Li J, ed. *Proceedings of the 4th International Conference on Power and Electrical Engineering*. Lecture Notes in Electrical Engineering. Singapore: Springer Nature Singapore, 2024: 289–99
309. Hong B, Gao L, Li C*, et al.* All-solid-state batteries designed for operation under extreme cold conditions. *Nature communications* 2025; **16:** 143
310. Raza S, Bashir T, Hayat A*, et al.* Recent progress and fundamentals of solid-state electrolytes for all solid-state rechargeable batteries: Mechanisms, challenges, and applications. *Journal of Energy Storage* 2024; **92**
311. Schmaltz T, Thielmann A. Solid-State Battery Roadmap 2035+. https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2022/SSB_Roadmap.pdf (accessed 08/04/2025)
312. Burton M, Narayanan S, Jagger. Techno-economic assessment of thin lithium metal anodes for solid-state batteries. https://doi.org/10.1038/s41560-024-01676-7. *Nature Energy* 2025; **10:** 135–47
313. Ilika. Model of Solid State Battery Pack Shows Weight and Cost Benefits Compared to Lithium-Ion. https://www.ilika.com/latest-news/model-of-solid-state-battery-pack-shows-weight-and-cost-benefits-compared-to-lithium-ion (accessed 08/05/2025)
314. PowerBank. How Solid State Batteries are Shaping the Future of EVs. https://powerbank.green/blogs/solid-state-battery.html (accessed 08/05/2025)
315. IATA. Battery Guidance Document Transport of Lithium Metal, Lithium Ion and Sodium Ion Batteries. https://www.iata.org/contentassets/05e6d8742b0047259bf3a700bc9d42b9/lithium-battery-guidance-document.pdf (accessed 08/05/2025)
316. Wikipedia. Solid-state battery. https://en.wikipedia.org/wiki/Solid-state_battery (accessed 08/05/2025)
317. Farzanian S, Shozib I, Sivadas N, Lacivita V, Wang Y, Tu QH. *Mechanical investigations of composite cathode degradation in all-solid-state-batteries*, 2023
318. Biçer E, Aksöz A, Bakar R*, et al.* Solid-State Batteries: Chemistry, Battery, and Thermal Management System, Battery Assembly, and Applications—A Critical Review. *Batteries* 2025; **11:** 212
319. Maisch M. World's first grid-scale, semi-solid-state energy storage project goes online. https://www.pv-magazine.com/2024/07/05/worlds-first-grid-scale-semi-solid-state-energy-storage-project-goes-online/ (accessed 08/05/2025)
320. University of Maryland. Maryland's first-ever solid-state battery pilot production line launches. https://mse.umd.edu/news/story/marylandrsquos-firstever-solidstate-battery-pilot-production-line-launches (accessed 08/05/2025)
321. Mims C. A Battery That Lasts 50% Longer Is Finally in Production. https://www.wsj.com/business/energy-oil/american-made-battery-76595c0f (accessed 0508.2025)
322. Farakhor A, Di Wu, Wang Y, Fang H. *A Novel Modular, Reconfigurable Battery Energy Storage System: Design, Control, and Experimentation*, Vol 9, 2023
323. Jacob M, Wissel K, Clemens O. Recycling of solid-state batteries—challenge and opportunity for a circular economy? *Materials Futures* 2024; **3:** 12101

324. Ahuis M, Doose S, Vogt D, Michalowski P, Zellmer S, Kwade A. Recycling of solid-state batteries. *Nature Energy* 2024; **9:** 373–85
325. Luo Y, Rao Z, Yang X, Wang C, Sun X, Li X. Safety concerns in solid-state lithium batteries: from materials to devices. *Energy & Environmental Science* 2024; **17:** 7543–65
326. Schmaltz T, Wicke T, Weymann L, *et al. Solid-State Battery Roadmap 2035+:* Fraunhofer-Gesellschaft, 2021
327. Farrell M. Is Yoshino REALLY a Solid State Battery? https://undecidedmf.com/is-yoshino-really-a-solid-state-battery/
328. Hasan SAU, Zahid MA, Park S, Yi J. Stability Challenges for a Highly Efficient Perovskite/Silicon Tandem Solar Cell: A Review. *Solar RRL* 2024; **8**
329. Diouf B, Muley A, Pode R. Issues, Challenges, and Future Perspectives of Perovskites for Energy Conversion Applications. *Energies* 2023; **16:** 6498
330. Baraneedharan P, Sekar S, Murugesan S, *et al.* Recent Advances and Remaining Challenges in Perovskite Solar Cell Components for Innovative Photovoltaics. *Nanomaterials (Basel, Switzerland)* 2024; **14**
331. Afroz M, Ratnesh RK, Srivastava S, Singh J. Perovskite solar cells: Progress, challenges, and future avenues to clean energy. *Solar Energy* 2025; **287:** 113205
332. Rani M, Khan MM, Numan A, *et al.* Breaking barriers: Addressing challenges in perovskite solar cell development. *Journal of Alloys and Compounds* 2025; **1010:** 177648
333. Cherubini A, Papini A, Vertechy R, Fontana M. Airborne Wind Energy Systems: A review of the technologies. *Renewable and Sustainable Energy Reviews* 2015; **51:** 1461–76
334. Roga S, Bardhan S, Kumar Y, Dubey SK. Recent technology and challenges of wind energy generation: A review. *Sustainable Energy Technologies and Assessments* 2022; **52:** 102239
335. Rishikesh J, Kruijff M, Schmehl R. Value-Driven System Design of Utility-Scale Airborne Wind Energy. *Energies* 2023; **16**
336. Epstein RI. A solid-state wind-energy transformer. *Applied Physics Letters* 2019; **115**
337. Kang H, Kook J, Lee J, Kim Y-K. A Novel Small-Scale Bladeless Wind Turbine Using Vortex-Induced Vibration and a Discrete Resonance-Shifting Module. *Applied Sciences* 2024; **14:** 8217
338. Bahadur I. Dynamic Modeling and Investigation of a Tunable Vortex Bladeless Wind Turbine. *Energies* 2022; **15:** 6773
339. Francis S, Umesh V, Shivakumar S. Design and Analysis of Vortex Bladeless Wind Turbine. *Materials Today: Proceedings* 2021; **47:** 5584–8
340. Halcium. Powershell. https://www.halcium.com/
341. Toja-Silva F, Colmenar-Santos A, Castro-Gil M. Urban wind energy exploitation systems: Behaviour under multidirectional flow conditions—Opportunities and challenges. *Renewable and Sustainable Energy Reviews* 2013; **24:** 364–78
342. Tahir MS, Tahir MB, Sagir M, Asiri AM, eds. *Lithium-Sulfur Batteries: Key Parameters, Recent Advances, Challenges and Applications,* 1st edn. Springer Tracts in Electrical and Electronics Engineering. Singapore: Springer Nature Singapore; Imprint Springer, 2024
343. Lyten. Lithium-Sulfur Batteries Powered by Lyten 3D Graphene™. https://lyten.com/products/lithium-sulfur-batteries/
344. Xue W, Miao L, Qie L, *et al.* Gravimetric and volumetric energy densities of lithium-sulfur batteries. *Current Opinion in Electrochemistry* 2017; **6:** 92–9
345. Zhong M, Guan J, Sun J, *et al.* A Cost- and Energy Density-Competitive Lithium-Sulfur Battery. *Energy Storage Materials* 2021; **41:** 588–98
346. Nakamura N, Ahn S, Momma T, Osaka T. Future potential for lithium-sulfur batteries. *Journal of Power Sources* 2023; **558:** 232566
347. Lyten. *Lyten Announces Plans to Build the World's First Lithium-Sulfur Battery Gigafactory in Nevada.* San Jose (Cal. USA), 2024

348. Asmare M, Zegeye M, Ketema A. Advancement of electrically rechargeable metal-air batteries for future mobility. *Energy Reports* 2024; **11:** 1199–211
349. Li Y, Lu J. Metal–Air Batteries: Will They Be the Future Electrochemical Energy Storage Device of Choice? *ACS Energy Letters* 2017; **2:** 1370–7
350. Olabi AG, Sayed ET, Wilberforce T, *et al.* Metal-Air Batteries—A Review. *Energies* 2021; **14:** 7373
351. Han Y, Liu B, Xiao Z, *et al.* Interface issues of lithium metal anode for high-energy batteries: Challenges, strategies, and perspectives. *InfoMat* 2021; **3:** 155–74
352. Onorati A, Payri R, Vaglieco BM, *et al.* The role of hydrogen for future internal combustion engines. *International Journal of Engine Research* 2022; **23:** 529–40
353. Stępień Z. A Comprehensive Overview of Hydrogen-Fueled Internal Combustion Engines: Achievements and Future Challenges. *Energies* 2021; **14:** 6504
354. Teoh YH, How HG, Le TD, *et al.* A review on production and implementation of hydrogen as a green fuel in internal combustion engines. *Fuel* 2023; **333:** 126525
355. Zhou F, Yu J, Wu C, Fu J, Liu J, Duan X. The application prospect and challenge of the alternative methanol fuel in the internal combustion engine. *The Science of the total environment* 2024; **913:** 169708
356. Nemmour A, Inayat A, Janajreh I, Ghenai C. Green hydrogen-based E-fuels (E-methane, E-methanol, E-ammonia) to support clean energy transition: A literature review,. *International Journal of Hydrogen Energy,* 2023; **48:** 29011–33
357. Shi J, Zhu Y, Feng Y, Yang J, Xia C. A Prompt Decarbonization Pathway for Shipping: Green Hydrogen, Ammonia, and Methanol Production and Utilization in Marine Engines. *Atmosphere* 2023; **14:** 584
358. European Commission. Small Modular Reactors explained. https://energy.ec.europa.eu/topics/nuclear-energy/small-modular-reactors/small-modular-reactors-explained_en
359. Testoni R, Bersano A, Segantin S. Review of nuclear microreactors: Status, potentialities and challenges. *Progress in Nuclear Energy* 2021; **138:** 103822
360. Vaya Soler A, Berthelemy M, Verma A, *et al. Small Modular Reactors: Challenges and Opportunities*, 2021
361. Vinoya CL, Ubando AT, Culaba AB, Chen W-H. State-of-the-Art Review of Small Modular Reactors. *Energies* 2023; **16:** 3224
362. Shobeiri E, Genco F, Hoornweg D, Tokuhiro A. Small Modular Reactor Deployment and Obstacles to Be Overcome. *Energies* 2023; **16:** 3468
363. Schlegel JP, Bhowmik PK. Small modular reactors. In: Wang J, Talabi S, Bilbao y Leon S, eds. *Nuclear power reactor designs*: *From history to advances*. Londan, San Diego, Cambridge: Elsevier Science & Technology, 2024: 283–308
364. Steigerwald B, Weibezahn J, Slowik M, Hirschhausen C von. Uncertainties in estimating production costs of future nuclear technologies: A model-based analysis of small modular reactors. *Energy* 2023; **281:** 128204
365. Chowdhury MS, Rahman KS, Selvanathan V, *et al.* Current trends and prospects of tidal energy technology. *Environment, development and sustainability* 2021; **23:** 8179–94
366. Masood Ahmad M, Kumar A, Ranjan R. Recent Developments of Tidal Energy as Renewable Energy: An Overview. In: Jha R, Singh VP, Singh V, Roy LB, Thendiyath R, eds. *River and Coastal Engineering*: *Hydraulics, Water Resources and Coastal Engineering,* 1st edn. Water Science and Technology Library. Vol 117. Cham: Springer International Publishing; Imprint Springer, 2022: 329–43
367. Lehmann M, Karimpour F, Goudey CA, Jacobson PT, Alam M-R. Ocean wave energy in the United States: Current status and future perspectives. *Renewable and Sustainable Energy Reviews* 2017; **74:** 1300–13
368. Lagoun MS, Benalia A, Benbouzid MEH. Ocean wave converters: State of the art and current status. In: *2010 IEEE International Energy Conference*: IEEE, 2010: 636–41
369. Nova Innovation. M100-D. https://novainnovation.com/products
370. Orbital Marine Power. O2-X. https://o2-x.orbitalmarine.com/

371. Perch Energy. Tidal Power Explained: What is Tidal Energy & Is It Renewable? https://www.perchenergy.com/blog/energy/tidal-power-explained-renewable-tidal-energy?utm_source=chatgpt.com
372. Guia RE, Ilagan AD, Sauz LG, Balinad EFJ. Pedal Power Generation: An Implementation of Stationary Bike Generator. *LPU-Laguna Journal of Engineering and Computer Studies* 2020; **4**
373. B B, R A, M.J V, Shiny V J. Real-Time Pedal-Operated System for Battery Charging. *Asian Journal of Applied Science and Technology* 2023; **07:** 93–9
374. Philip R. Performance Analysis of Human Energized Battery Charger. *International Journal for Research in Applied Science and Engineering Technology* 2022; **10:** 385–8
375. Akpan WA, Nyaudo, II, Oboh AE, Akpan UE. Pedaling and cranking operated power generator for small home appliances. *International Journal of Science and Research Archive* 2024; **13:** 1841–8
376. Wang L, Fei Z, Qi Y*, et al.* Overview of Human Kinetic Energy Harvesting and Application. *ACS Applied Energy Materials* 2022; **5:** 7091–114
377. Sage V, Patel J, Hazewinkel P*, et al.* Recent progress and techno-economic analysis of liquid organic hydrogen carriers for Australian renewable energy export – A critical review. *International Journal of Hydrogen Energy* 2024; **56:** 1419–34
378. Le T-H, Tran N, Lee H-J. Development of Liquid Organic Hydrogen Carriers for Hydrogen Storage and Transport. *International Journal of Molecular Sciences* 2024; **25:** 1359
379. Sathe RY, Dhilip Kumar TJ, Ahuja R. Furtherance of the material-based hydrogen storage based on theory and experiments. *International Journal of Hydrogen Energy* 2023; **48:** 12767–95
380. Dell'Aversano S, Villante C, Gallucci K, Vanga G, Di Giuliano A. E-Fuels: A Comprehensive Review of the Most Promising Technological Alternatives towards an Energy Transition. *Energies* 2024: 3995
381. Pasini G, Lutzemberger G, Ferrari L. Renewable Electricity for Decarbonisation of Road Transport: Batteries or E-Fuels? *Batteries* 2023; **9:** 135
382. Shi K, Guan B, Zhuang Z*, et al.* Perspectives and Outlook of E-fuels: Production, Cost Effectiveness, and Applications. *Energy & Fuels* 2024; **38:** 7665–92
383. Zhang X, Gao Z, Zhou B*, et al.* Advanced Compressed Air Energy Storage Systems: Fundamentals and Applications. *Engineering* 2024; **34:** 246–69
384. Burian O, Dančová P. Compressed Air Energy Storage (CAES) and Liquid Air Energy Storage (LAES) Technologies—A Comparison Review of Technology Possibilities. *Processes* 2023; **11:** 3061
385. An D, Li Y, Lin X, Teng S. Analysis of compression/expansion stage on compressed air energy storage cogeneration system. *Frontiers in Energy Research* 2023; **11**
386. Olabi, AG, Wilberforce T, Ramadan M, Abdelkareem MA, Alami AH. Compressed air energy storage systems: Components and operating parameters – A review. *Journal of Energy Storage* 2021; **34**
387. Lakshmi KCS, Vedhanarayanan B. High-Performance Supercapacitors: A Comprehensive Review on Paradigm Shift of Conventional Energy Storage Devices. *Batteries* 2023; **9:** 202
388. şahin M, Blaabjerg F, Sangwongwanich A. A Comprehensive Review on Supercapacitor Applications and Developments. *Energies* 2022; **15:** 674
389. Li Q, Horn M, Wang Y, MacLeod J, Motta N, Liu J. A Review of Supercapacitors Based on Graphene and Redox-Active Organic Materials. *Materials (Basel, Switzerland)* 2019; **12**
390. Novotny V, Basta V, Smola P, Spale J. Review of Carnot Battery Technology Commercial Development. *Energies* 2022; **15:** 647
391. Vecchi A, Knobloch K, Liang T*, et al.* Carnot Battery development: A review on system performance, applications and commercial state-of-the-art,. *Journal of Energy Storage,* 2022; **55:** 105782

392. Dumont O, Frate GF, Pillai A, Lecompte S, De Paepe M, Lemort V. Carnot battery technology : a state-of-the-art review. *Journal of Energy Storage*; **2020:** 101756
393. Li X, Palazzolo A. A review of flywheel energy storage systems: state of the art and opportunities. *Journal of Energy Storage* 2022; **46:** 103576
394. Olabi AG, Wilberforce T, Abdelkareem MA, Ramadan M. Critical Review of Flywheel Energy Storage System. *Energies* 2021; **14:** 2159
395. Xu K, Guo Y, Lei G, Zhu J. A Review of Flywheel Energy Storage System Technologies. *Energies* 2023; **16:** 6462
396. Fraunhofer IPT. *Discussion Paper Future energy storage system for mobility applications*, 2020
397. Koohi-Fayegh S, Rosen MA. A review of energy storage types, applications and recent developments. *Journal of Energy Storage* 2020; **27:** 101047

Annex 1

Powerbase Patent Analysis – Results

Crystalline silicon photovoltaic cells

Search

Search Query: SPUB=(TAC=("**Crystalline silicon***" AND "**photovoltaic cell***")

OR (TAC=("***crystalline Silicon Cell***") AND (TAC=("**photovolt***" OR "**solar***")

OR IC=(**H10F10**))) AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 673

Publications: 719

Crystalline silicon photovoltaic cells

World actors

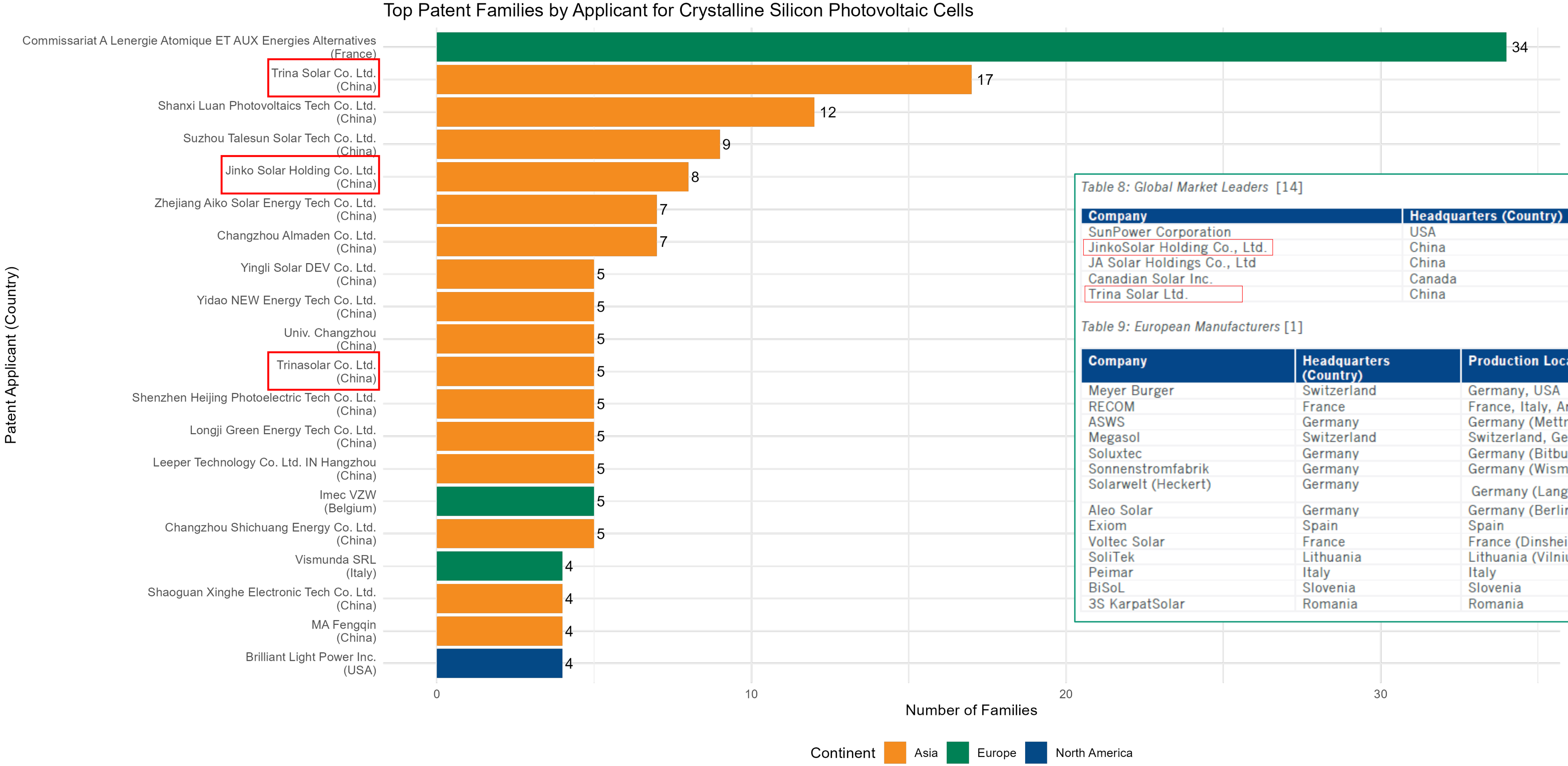


Table 8: Global Market Leaders [14]

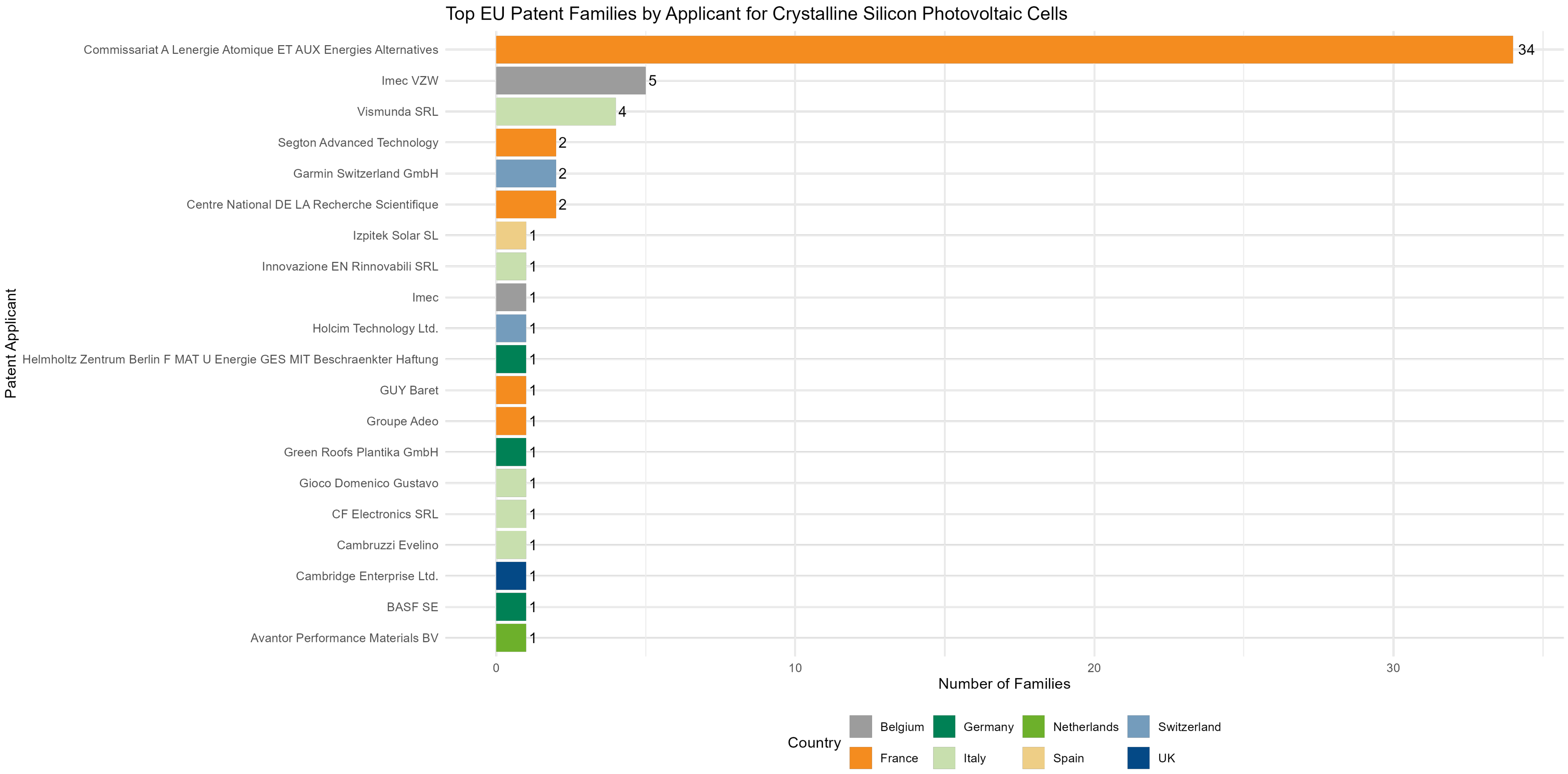
Company	Headquarters (Country)
SunPower Corporation	USA
JinkoSolar Holding Co., Ltd.	China
JA Solar Holdings Co., Ltd	China
Canadian Solar Inc.	Canada
Trina Solar Ltd.	China

Table 9: European Manufacturers [1]

Company	Headquarters (Country)	Production Locations
Meyer Burger	Switzerland	Germany, USA
RECOM	France	France, Italy, Armenia
ASWS	Germany	Germany (Mettmann)
Megasol	Switzerland	Switzerland, Germany
Soluxtec	Germany	Germany (Bitburg)
Sonnenstromfabrik	Germany	Germany (Wismar)
Solarwelt (Heckert)	Germany	Germany (Langenwetzendorf)
Aleo Solar	Germany	Germany (Berlin)
Exiom	Spain	Spain
Voltec Solar	France	France (Dinsheim-sur-Bruche)
SoliTek	Lithuania	Lithuania (Vilnius)
Peimar	Italy	Italy
BiSoL	Slovenia	Slovenia
3S KarpatSolar	Romania	Romania

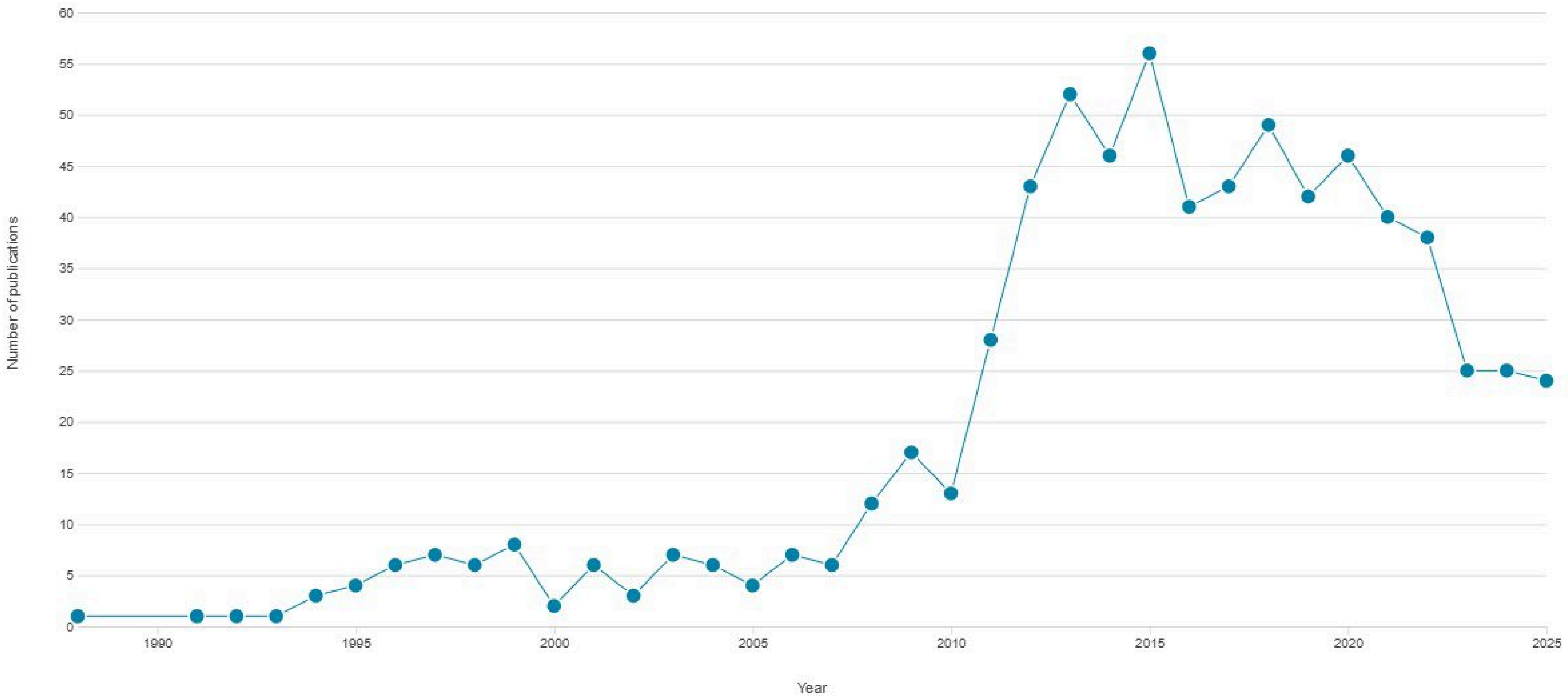
Crystalline silicon photovoltaic cells

Europe actors



Fraunhofer INT

Crystalline silicon photovoltaic cells
Publications



Document Set: Crystalline Silcon Cell
Date: June 27, 2025
Source: KATI developed by Fraunhofer INT

Thin-Film Photovoltaic

Search

Search Query: SPUB=(TAC=("**Thin-Film Photovoltaic***" OR "**Thin-Film Solar Cell***") AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 3466

Publications: 12831

Commercial of the Shelf technology

Thin-Film Photovoltaic

World actors

Weitere:

Solar Frontier KK (Japan): 14

Solopower Systems Inc. (USA): 8

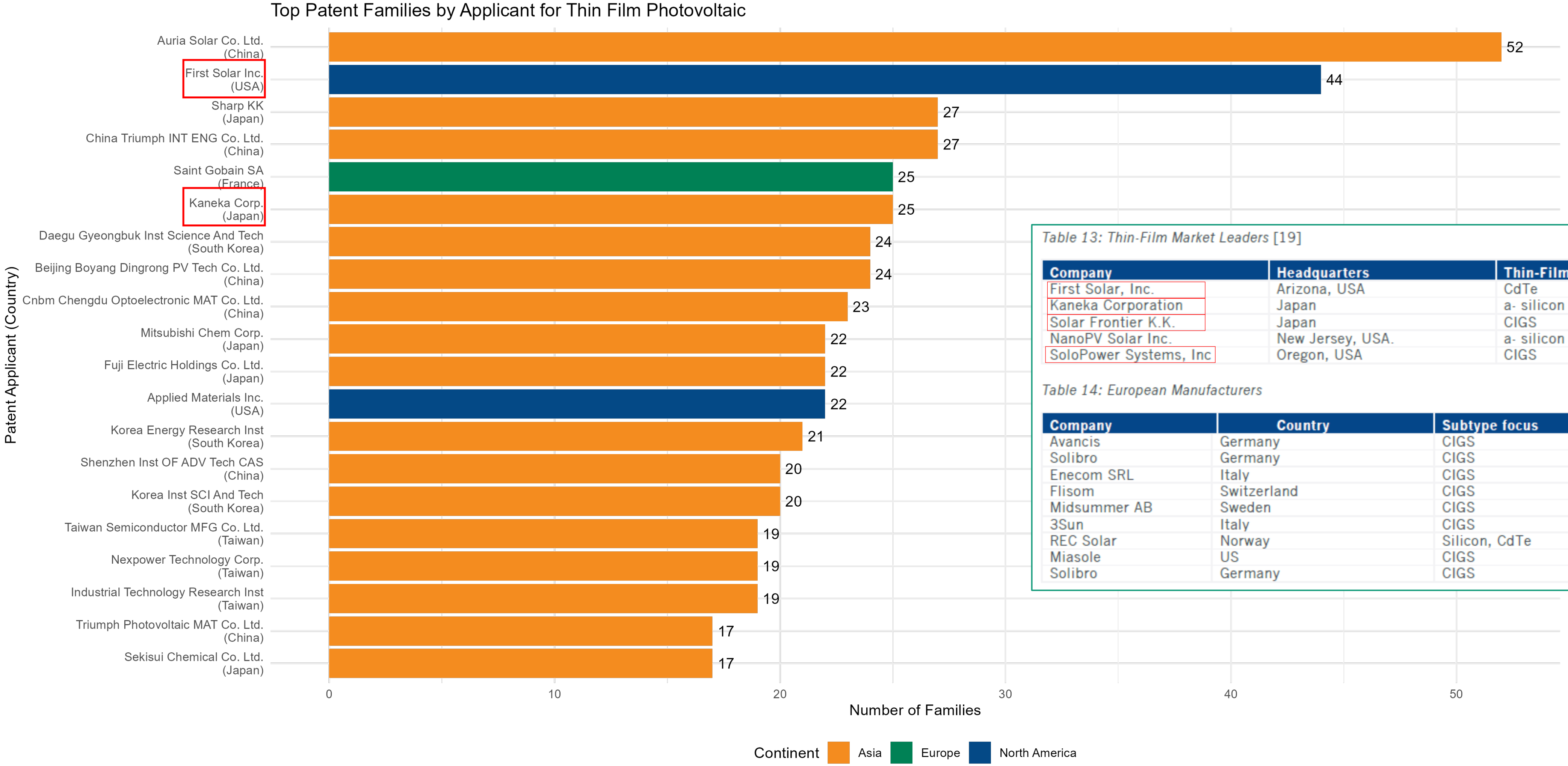


Table 13: Thin-Film Market Leaders [19]

Company	Headquarters	Thin-Film PV Focus
First Solar, Inc.	Arizona, USA	CdTe
Kaneka Corporation	Japan	a- silicon
Solar Frontier K.K.	Japan	CIGS
NanoPV Solar Inc.	New Jersey, USA.	a- silicon
SoloPower Systems, Inc	Oregon, USA	CIGS

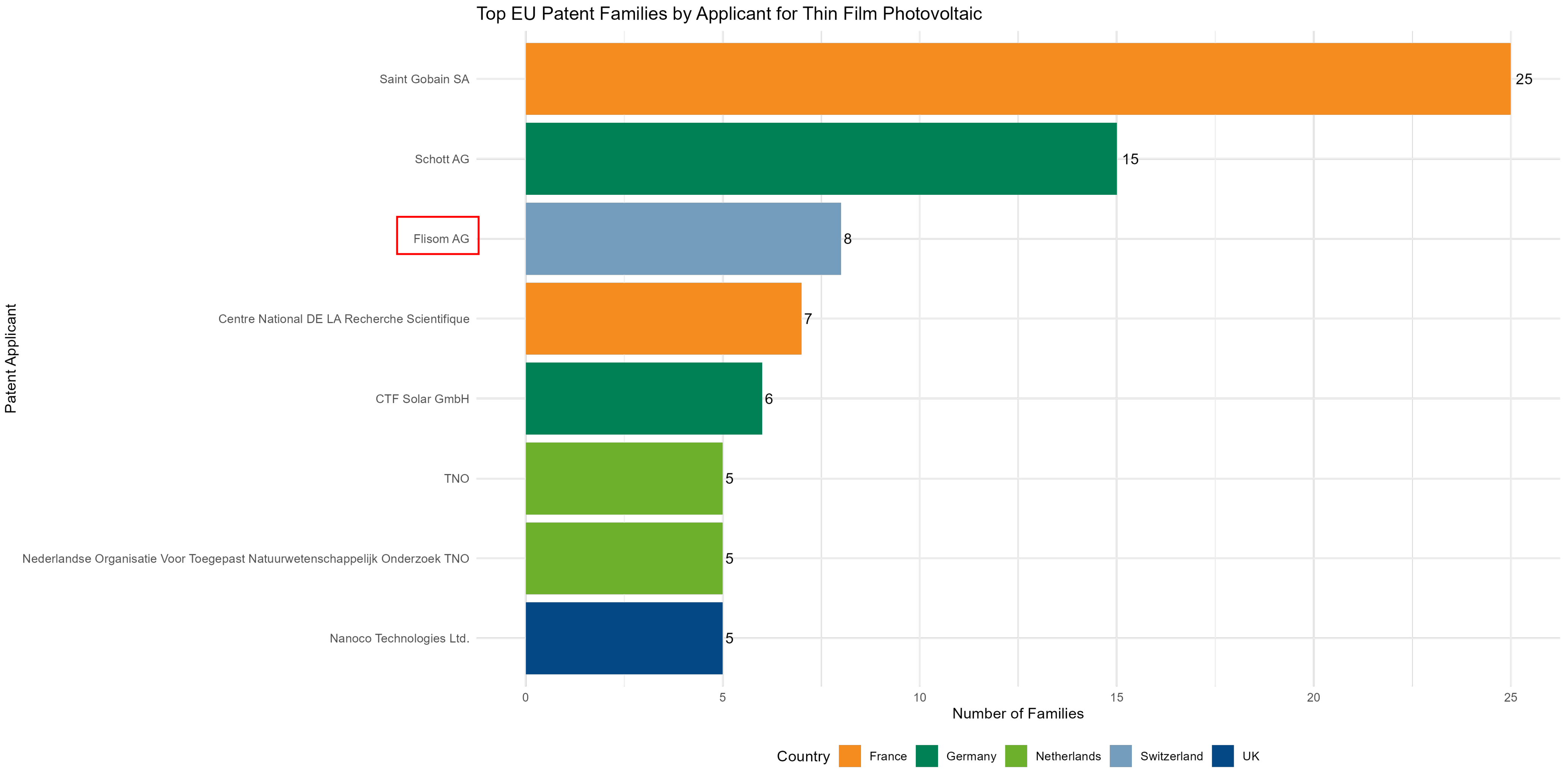
Table 14: European Manufacturers

Company	Country	Subtype focus
Avancis	Germany	CIGS
Solibro	Germany	CIGS
Enecom SRL	Italy	CIGS
Flisom	Switzerland	CIGS
Midsummer AB	Sweden	CIGS
3Sun	Italy	CIGS
REC Solar	Norway	Silicon, CdTe
Miasole	US	CIGS
Solibro	Germany	CIGS

Fraunhofer INT

Thin-Film Photovoltaic

Europe actors

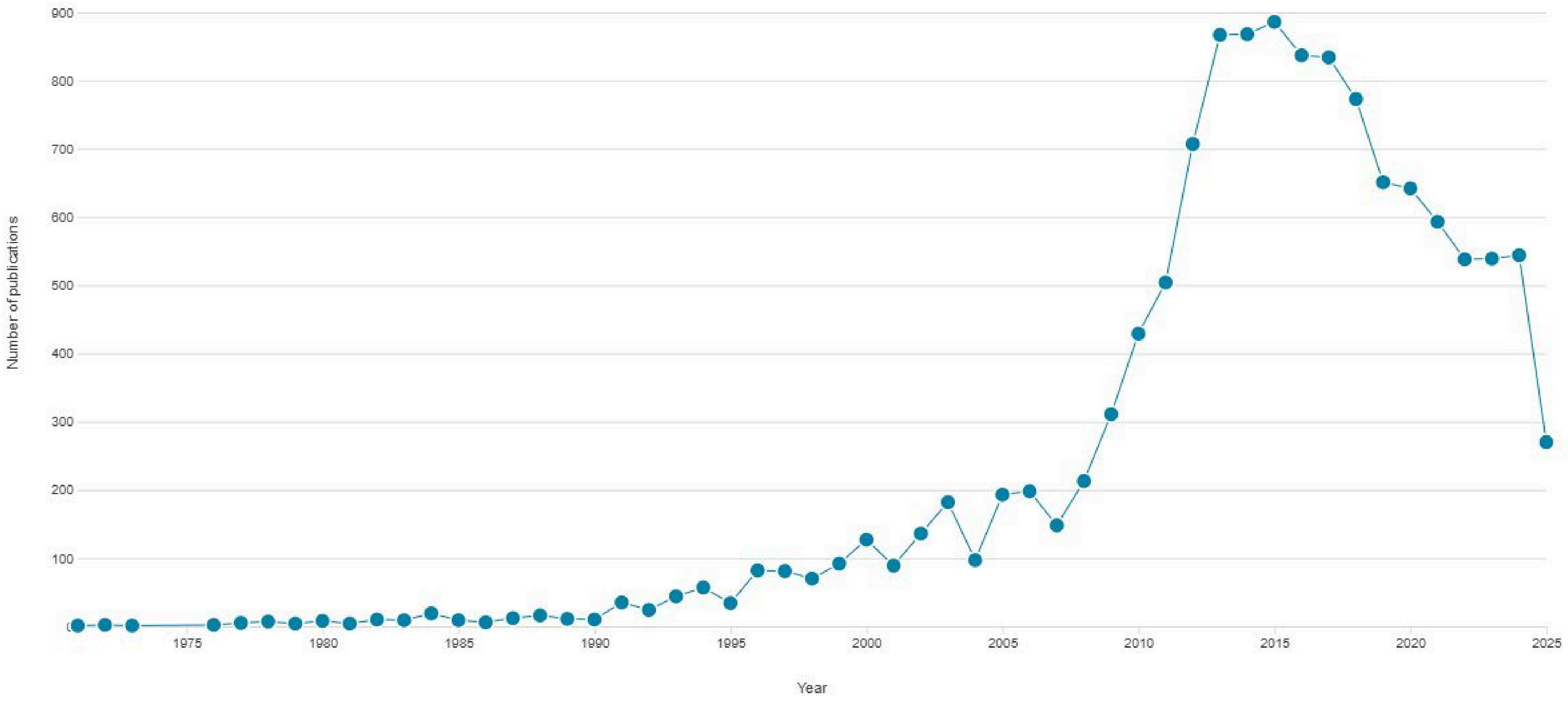


Fraunhofer INT

Commercial of the Shelf technology

Thin-Film Photovoltaic

Publications



Document Set: Thin-Film Photovoltaic
Date: June 27, 2025
Source: KATI developed by Fraunhofer INT

Small-Hydro-Generators

Search

Search Query: SPUB=((IC=(**F03B13** or **F03B17**) AND TAC="**Generator***")

OR TAC=("**Small Hydro Generator***" OR "**Micro Hydro***" OR "**Small Hydro Power**" OR "**Run-of-River Hydro**" OR "**Hydropower System***") AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

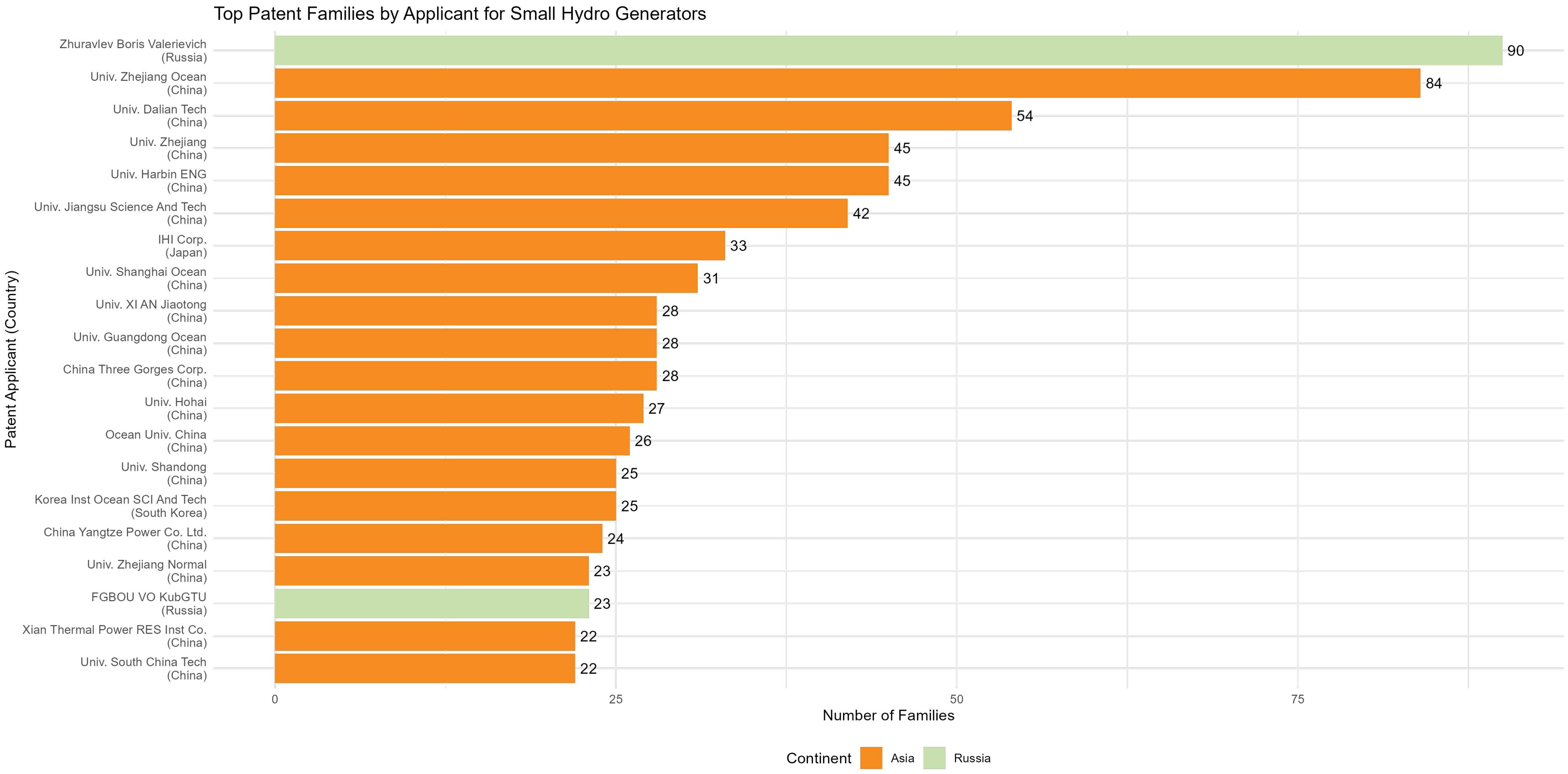
Patentfamilies: 10728

Publications: 2794

Commercial of the Shelf technology

Small-Hydro-Generators

World actors (keine Akteure im pdf)

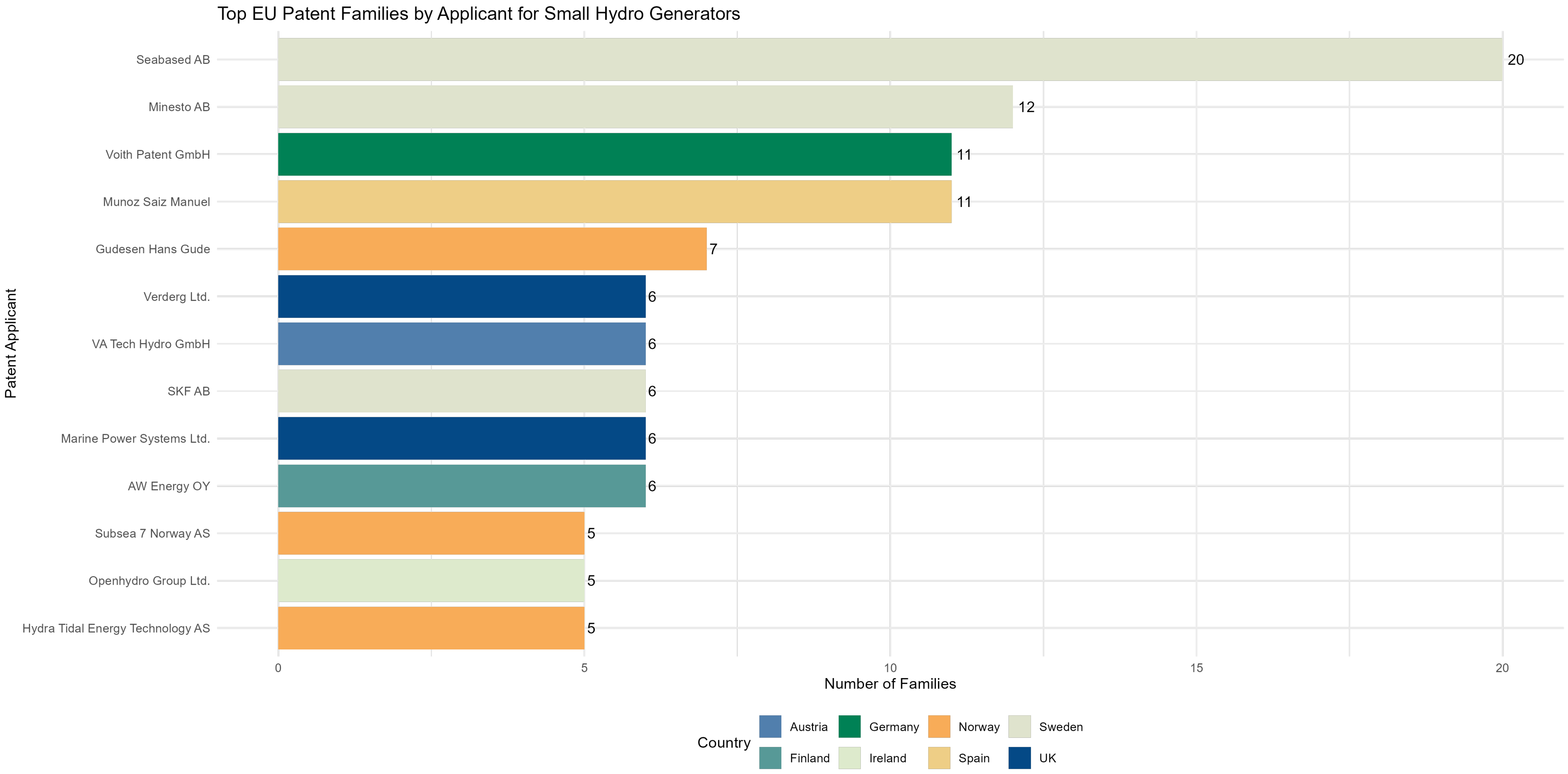


Fraunhofer INT

Commercial of the Shelf technology

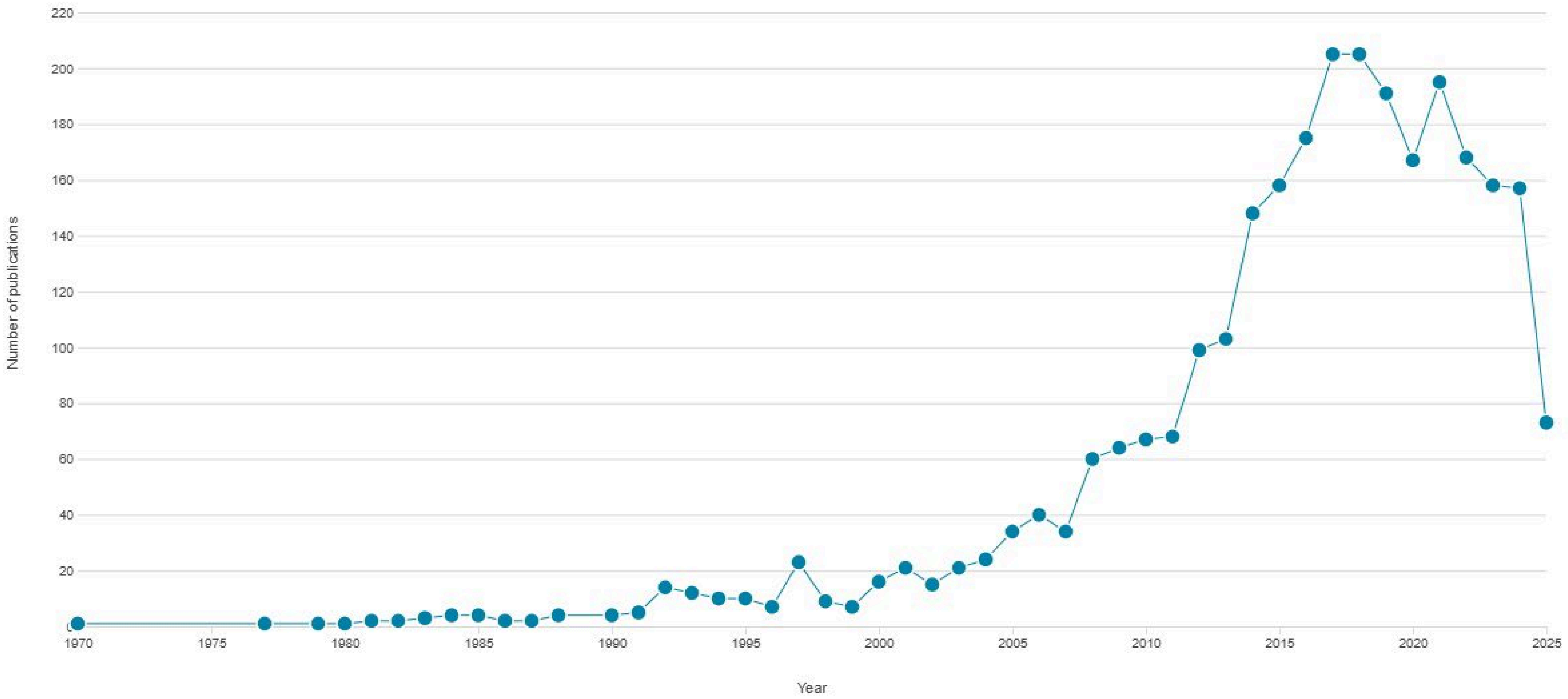
Small-Hydro-Generators

Europe actors



Fraunhofer INT

Small-Hydro-Generators
Publications



Document Set: Small Hydro Generators
Date: June 27, 2025
Source: KATI developed by Fraunhofer INT

Small wind turbines

Search

Search Query: SPUB=(TAC=("**Small Wind Turbines**" OR "**Micro Wind Turbines**"

OR ("**Small Wind Power**" AND "**generat***"))

OR (TAC=(**small*** OR **micro***) AND IC=**F03D** AND TAC="**generat**") AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

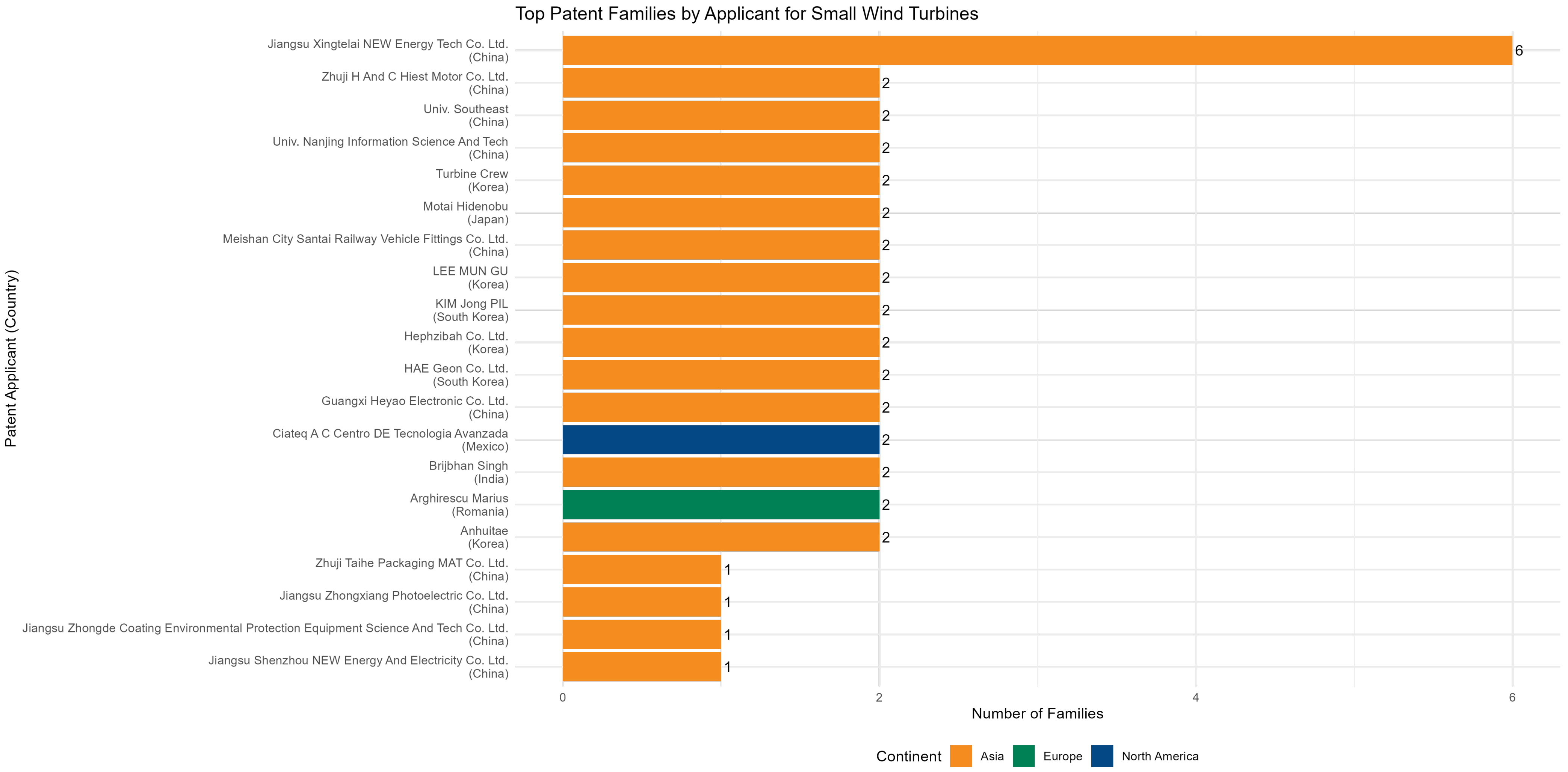
Patentfamilies: 246

Publications: 861

Commercial of the Shelf technology

Small wind turbines

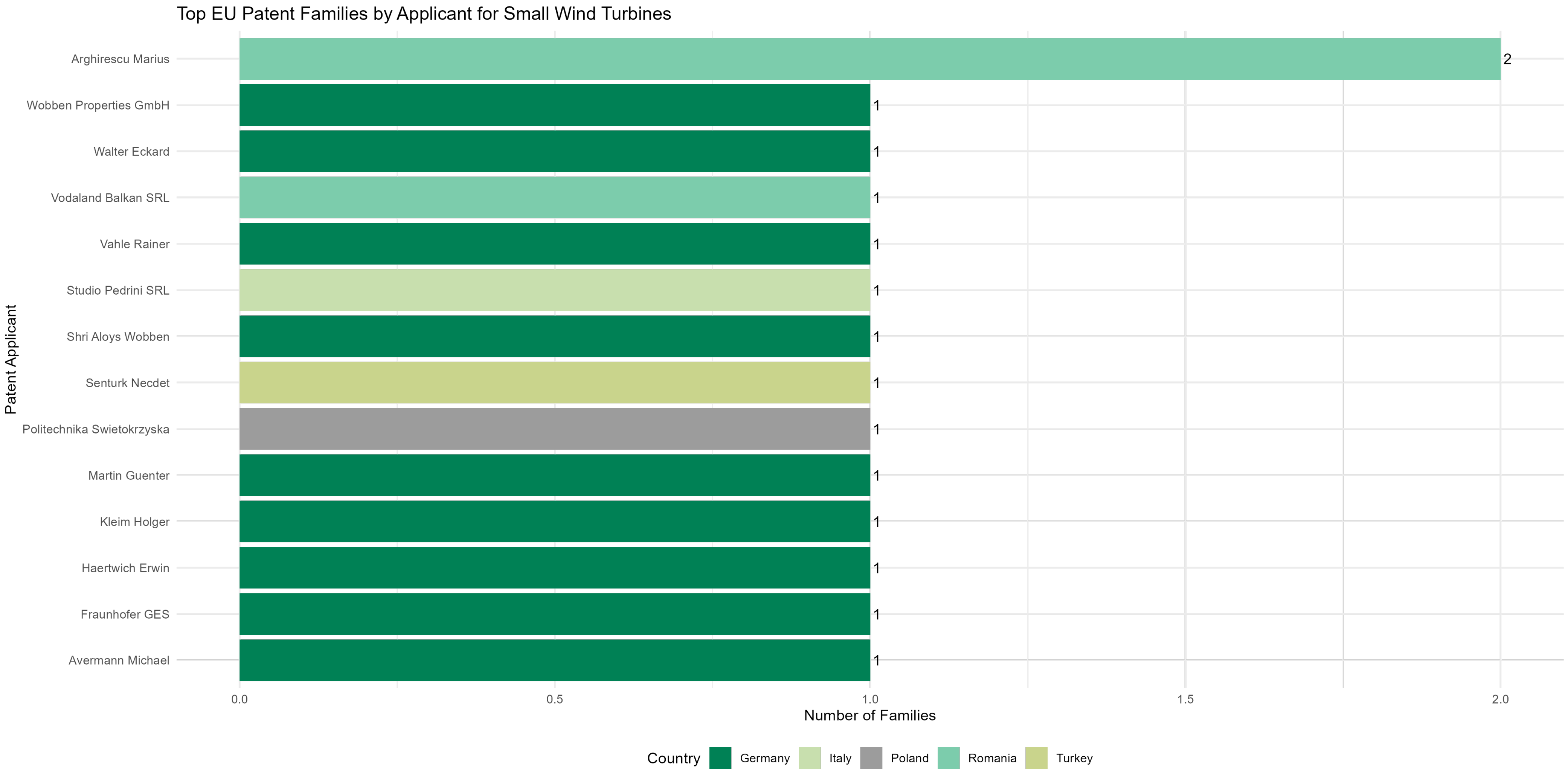
World actors (keine Akteure im pdf)



Fraunhofer INT

Small wind turbines

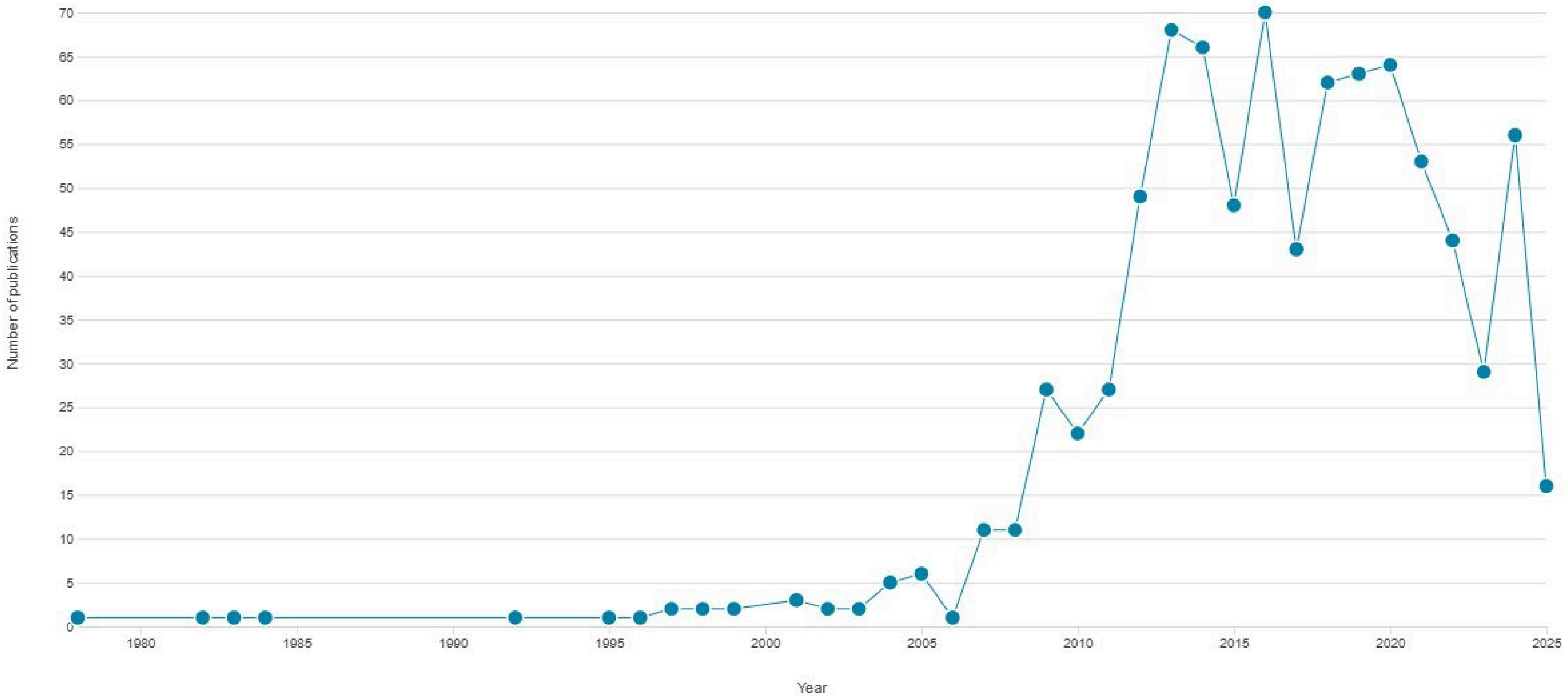
Europe actors



Fraunhofer INT

Small wind turbines

Publications



Document Set: Small wind turbines
Date: June 27, 2025
Source: KATI developed by Fraunhofer INT

Commercial of the Shelf technology

Lithium-ion Batteries

Search

Search Query: SPUB=(TAC=("**lithium-ion batter***" OR ("**Lithium Nickel Manganese Cobalt Oxid***" OR "**Lithium Nickel Cobalt Aluminum Oxid***" OR "**Lithium Iron Phosphate**" OR "**Lithium Manganese Oxide**") AND "**batter***")

OR (TAC=("**NMC**" OR "**NCA**" OR "**LFP**" OR "**LMO**") AND IC="**Y02E60/10**"))

AND IC8=(**H01M10** OR **H01M4** OR **H01M50** OR **H01M2** OR **H01G11** OR **H01M6** OR **H01B1** OR **H01G9** OR **H01M8** OR **H01M12** OR **C01B32** OR **C01B25** OR **C01G53** OR **C01B33** OR **C01D15** OR **C01G45** OR **C01G51** OR **C01B31** OR **C01G49** OR **C01G23** OR **G01R31** OR **G01N27** OR **G01R1** OR **G01R19** OR **G01N3** OR **H02J7** OR **H02H7** OR **H02J3** OR **H02J9** OR **H02J1** OR **H02M3** OR **H02S40** OR **H02M7** OR **H02J50** OR **H02J15**)

AND ALIVE=(YES)

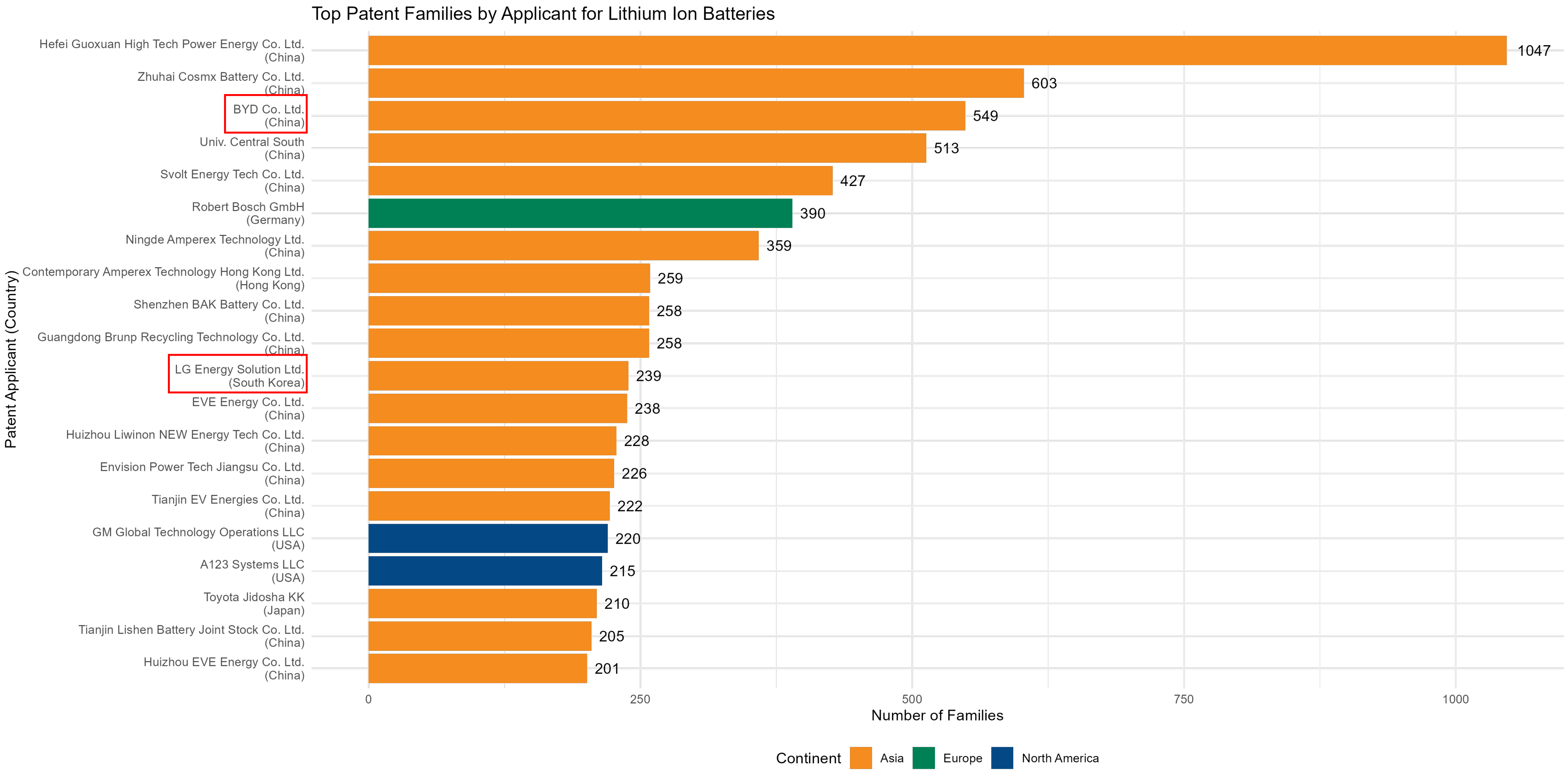
Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 56876

Publications: 103402

Lithium-ion Batteries

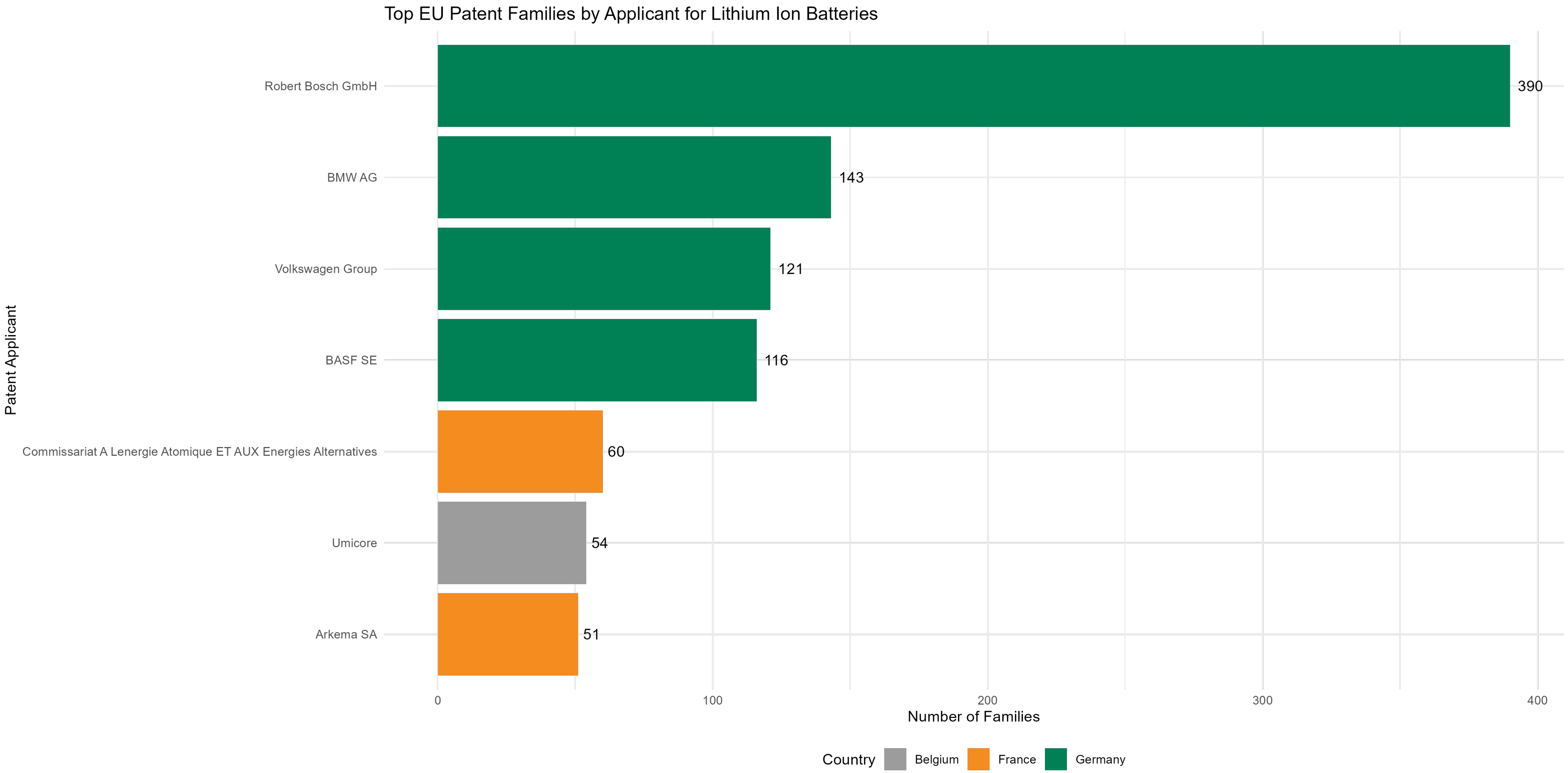
World actors



Fraunhofer INT

Lithium-ion Batteries

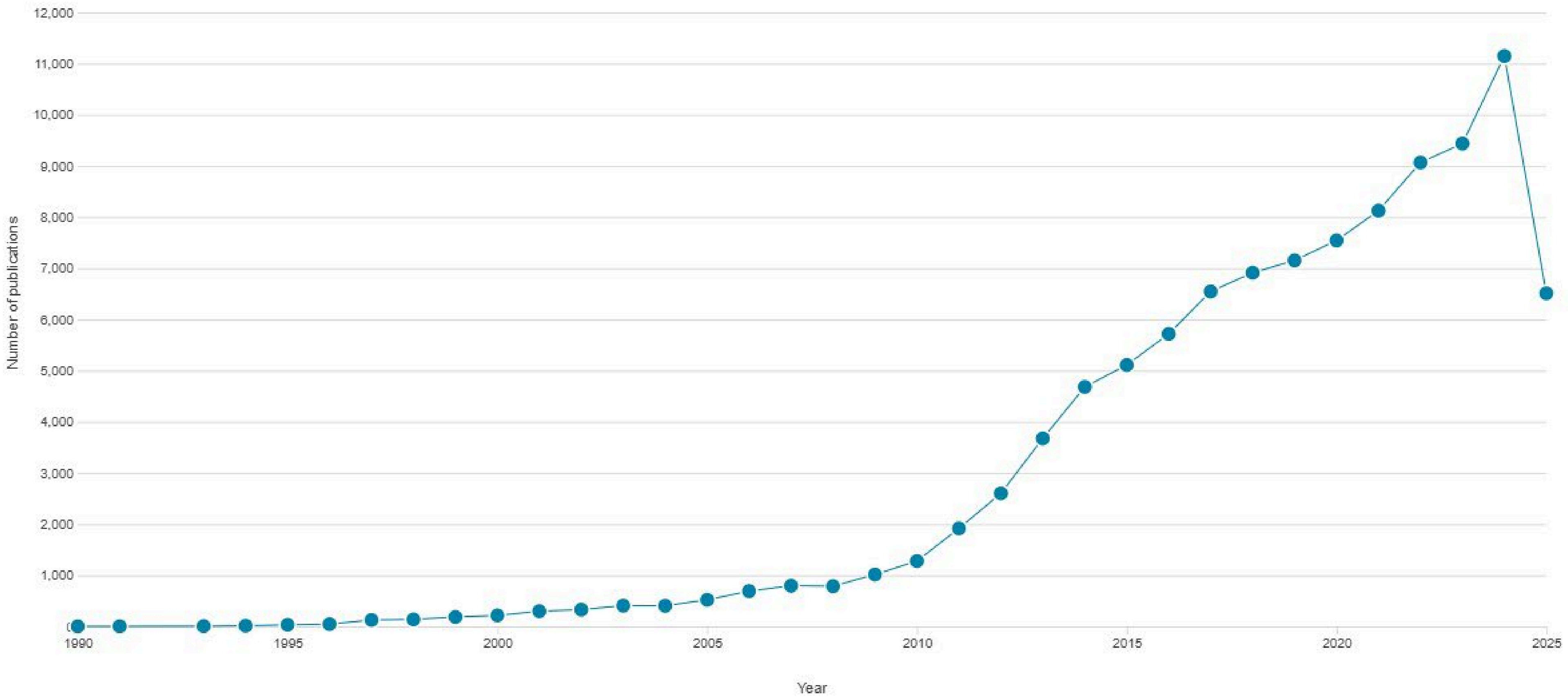
Europe actors



Commercial of the Shelf technology

Lithium-ion Batteries

Publications



Document Set: Lithium Ion Battery
Date: June 27, 2025
Source: KATI developed by Fraunhofer INT

Hydrogen Storage
Search

Search Query: SPUB=(CPC=(**Y02E60/32**) AND ALIVE=(YES))

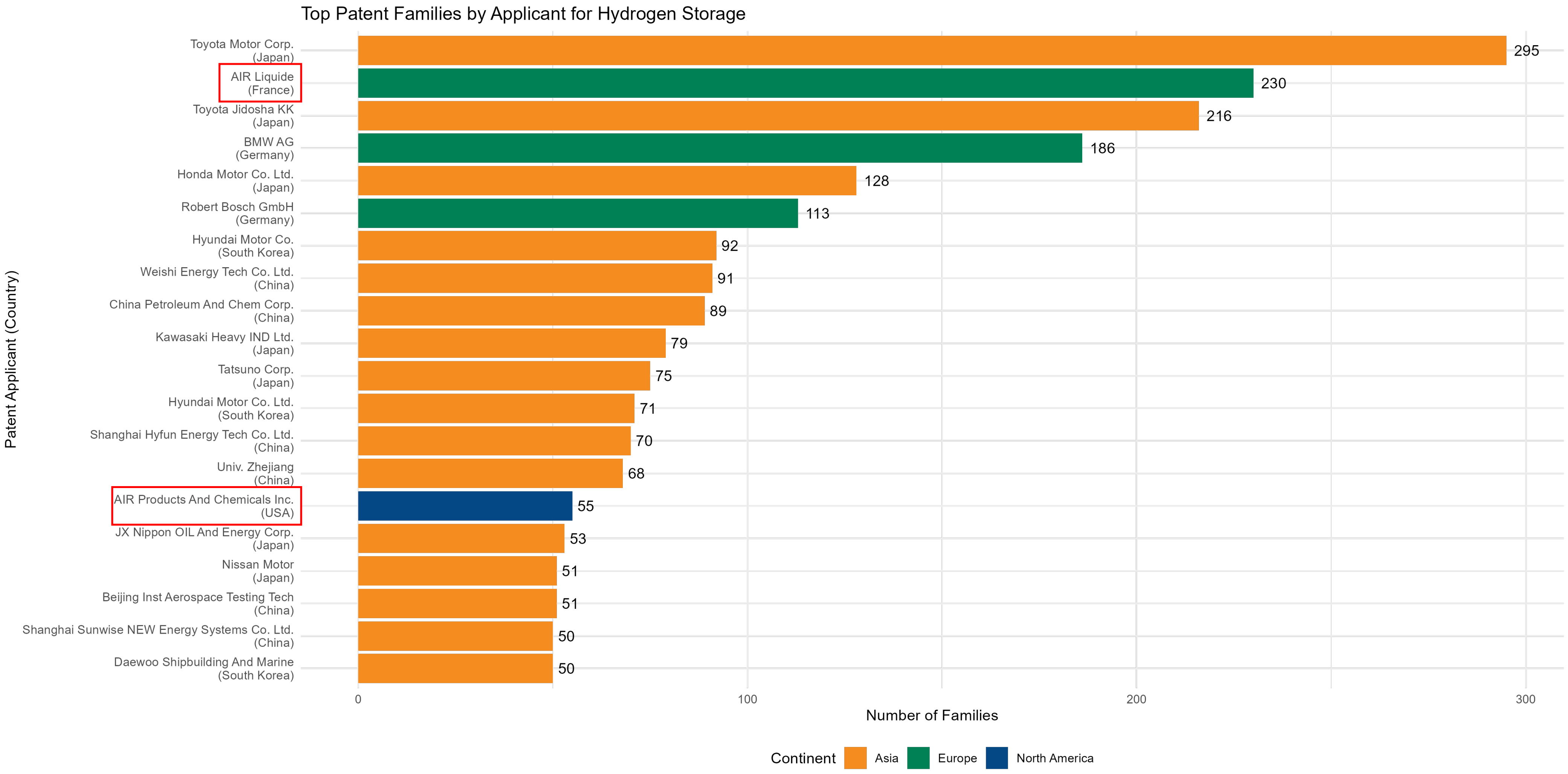
Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 12940

Publications: 37033

Hydrogen Storage

World actors



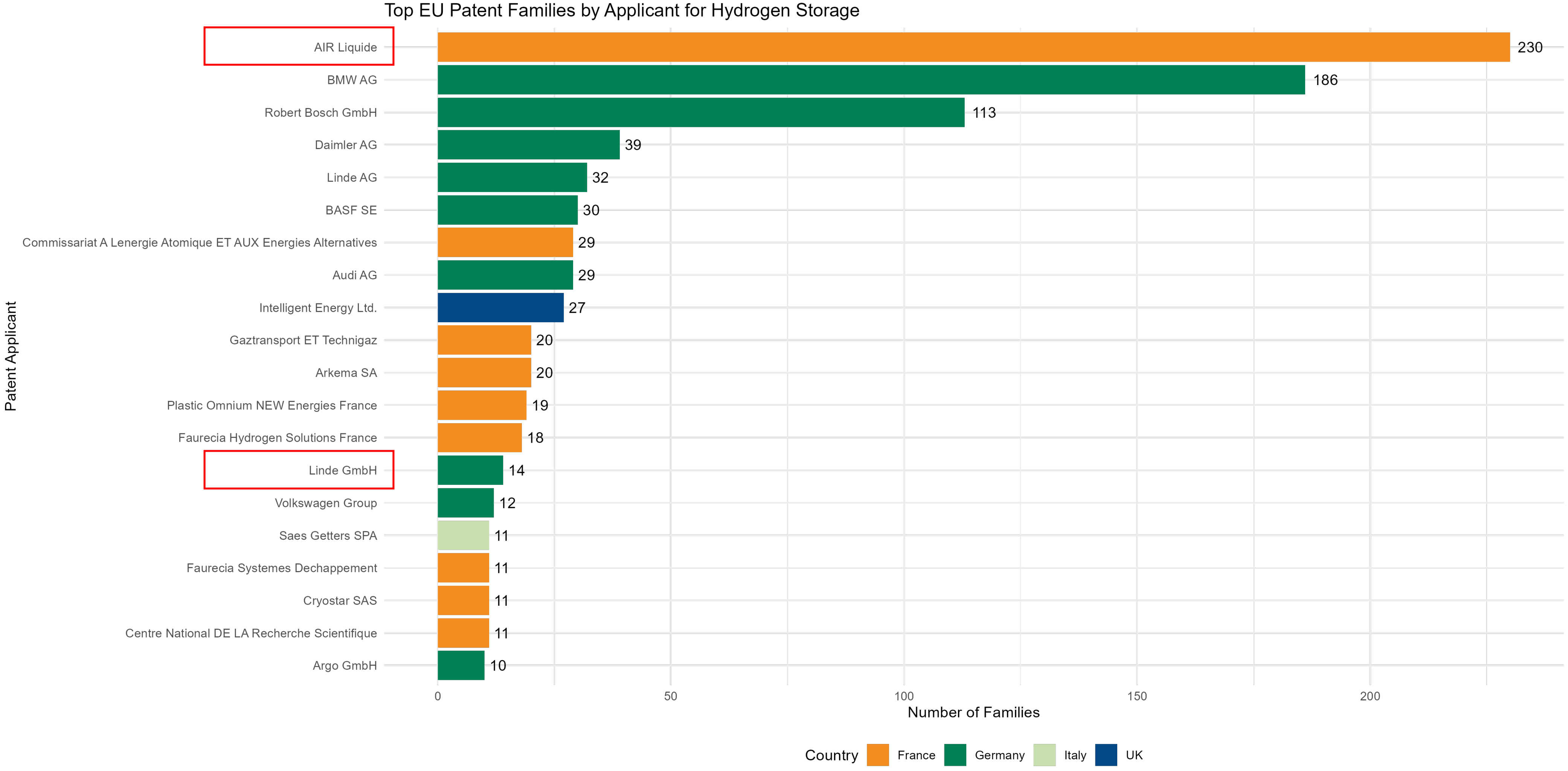
Fraunhofer INT

Commercial of the Shelf technology

Hydrogen Storage
Europe actors

Weitere:

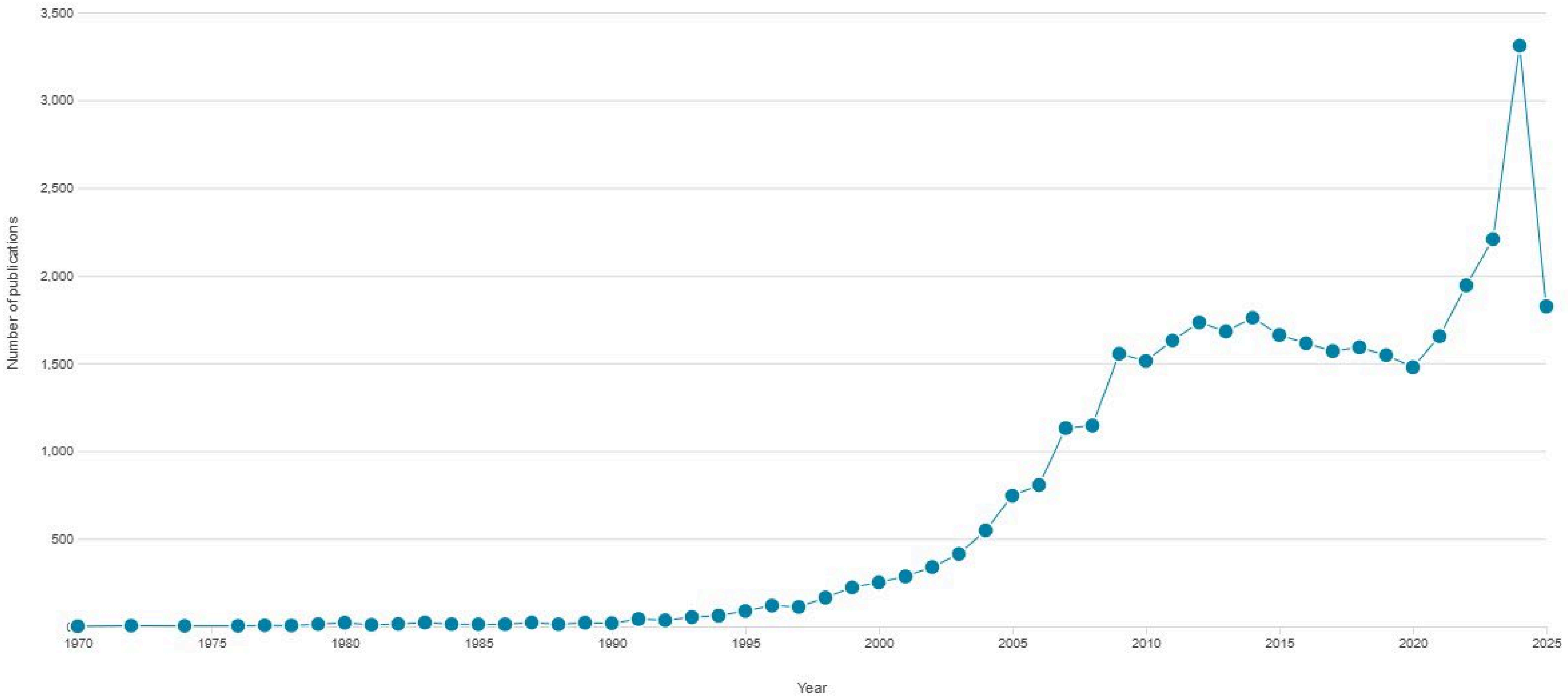
Nel (Norway): 10



Fraunhofer INT

Hydrogen Storage

Publications



Document Set: Hydrogen storage
Date: June 27, 2025
Source: KATI developed by Fraunhofer INT

Flow-batteries
Search

Search Query: SPUB=(TAC=("**flow batter***" OR "**Vanadium Redox Flow Batter***" OR "**Zinc-Bromine Flow Batter***" OR "**Hydrogen-Bromine Flow Batter***" OR ("**Iron Chromium**" AND "**batter***") OR "**Vanadium-Bromine Batter***" OR "**All-Iron-Flow Batter***" OR "**Organic Redox Flow Batter***" OR ("**Membraneless-Flow**" AND "**batter***"))

OR (IC8=**H01M8/18** AND TAC="**redox**")

AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 6521

Publications: 8576

Flow-batteries

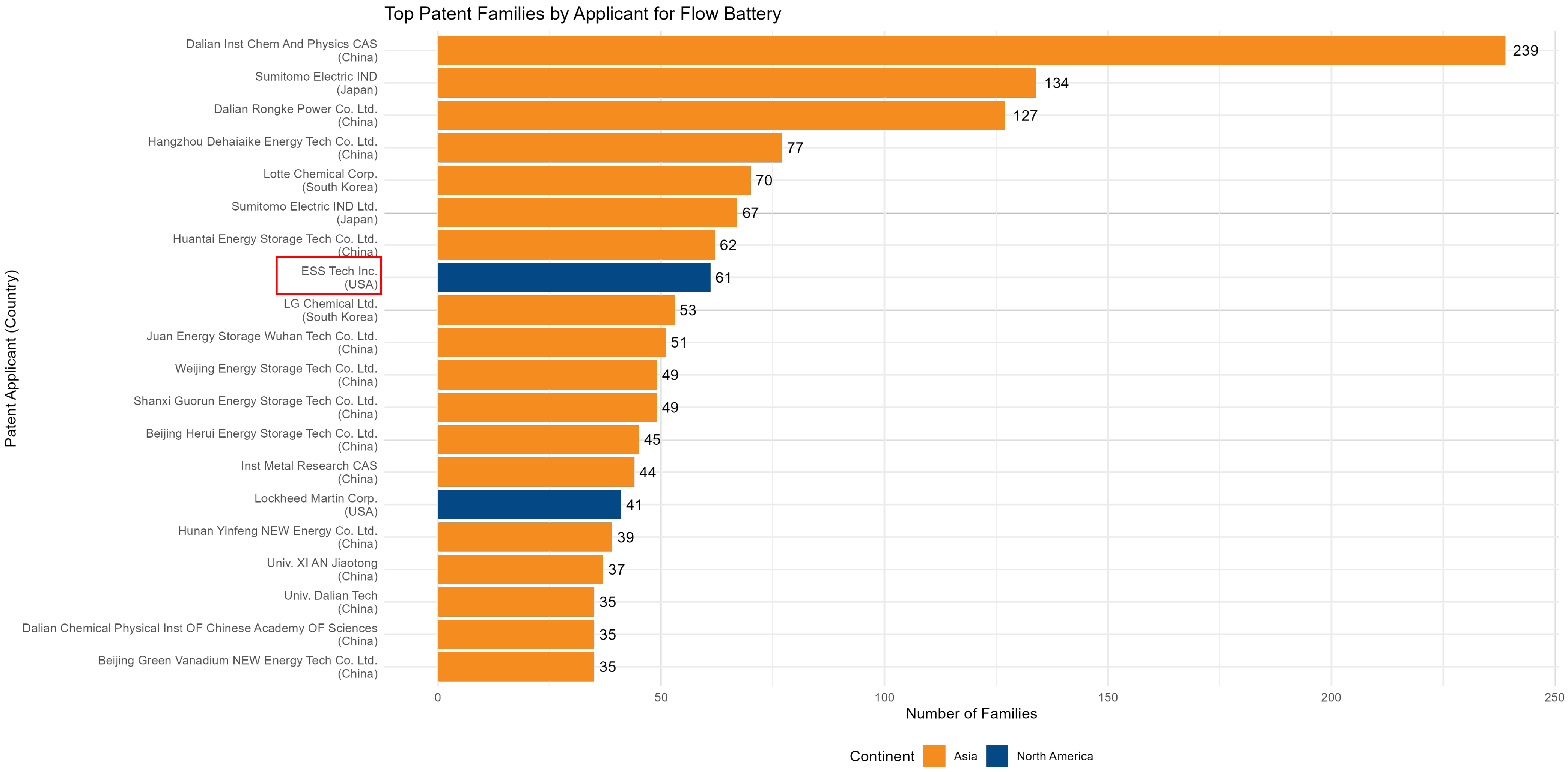
World actors

Commercial of the Shelf technology

Weitere:

Primus Power Corporation (USA): 10

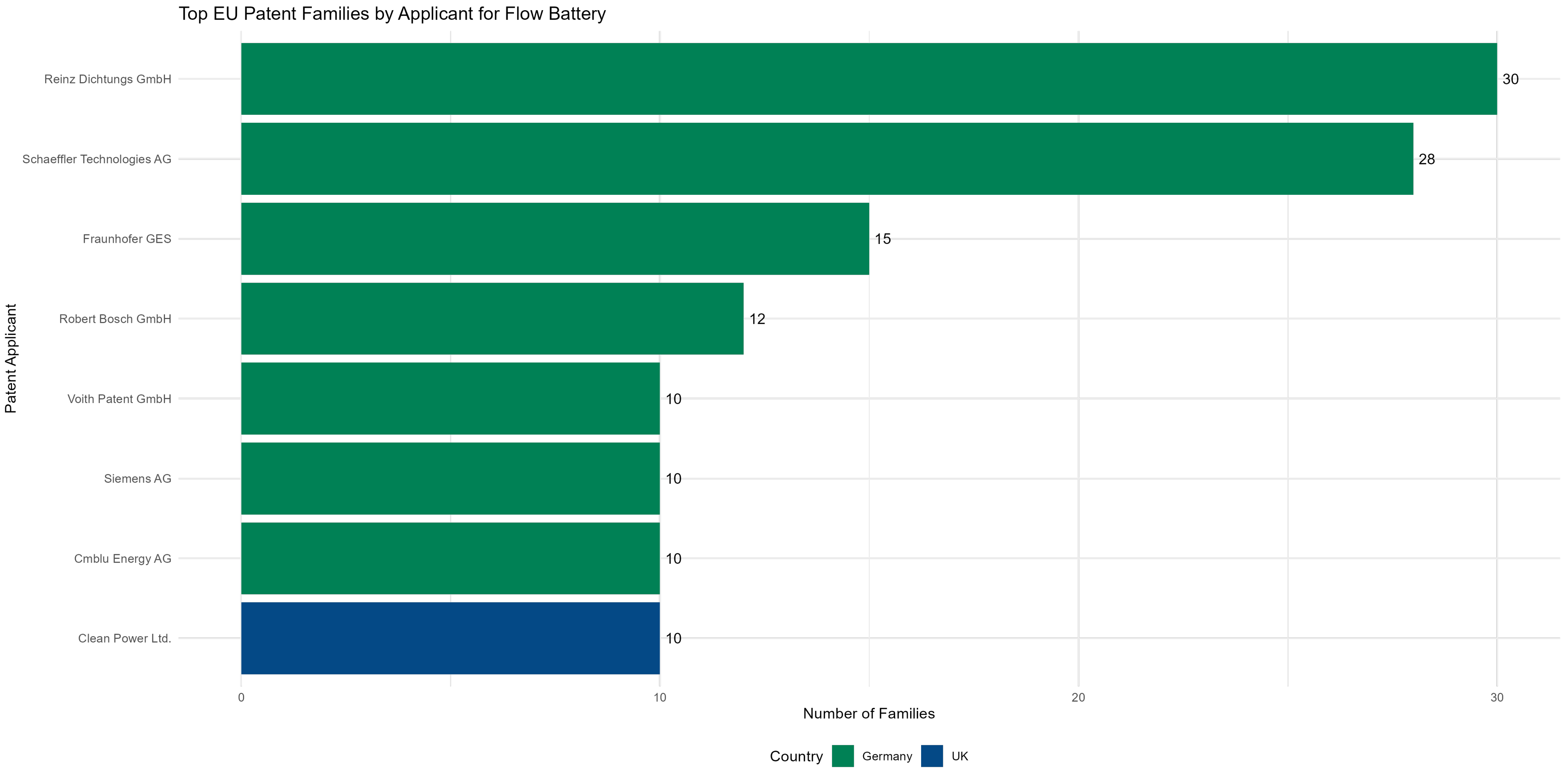
VRB Energy (USA): 21



Fraunhofer INT

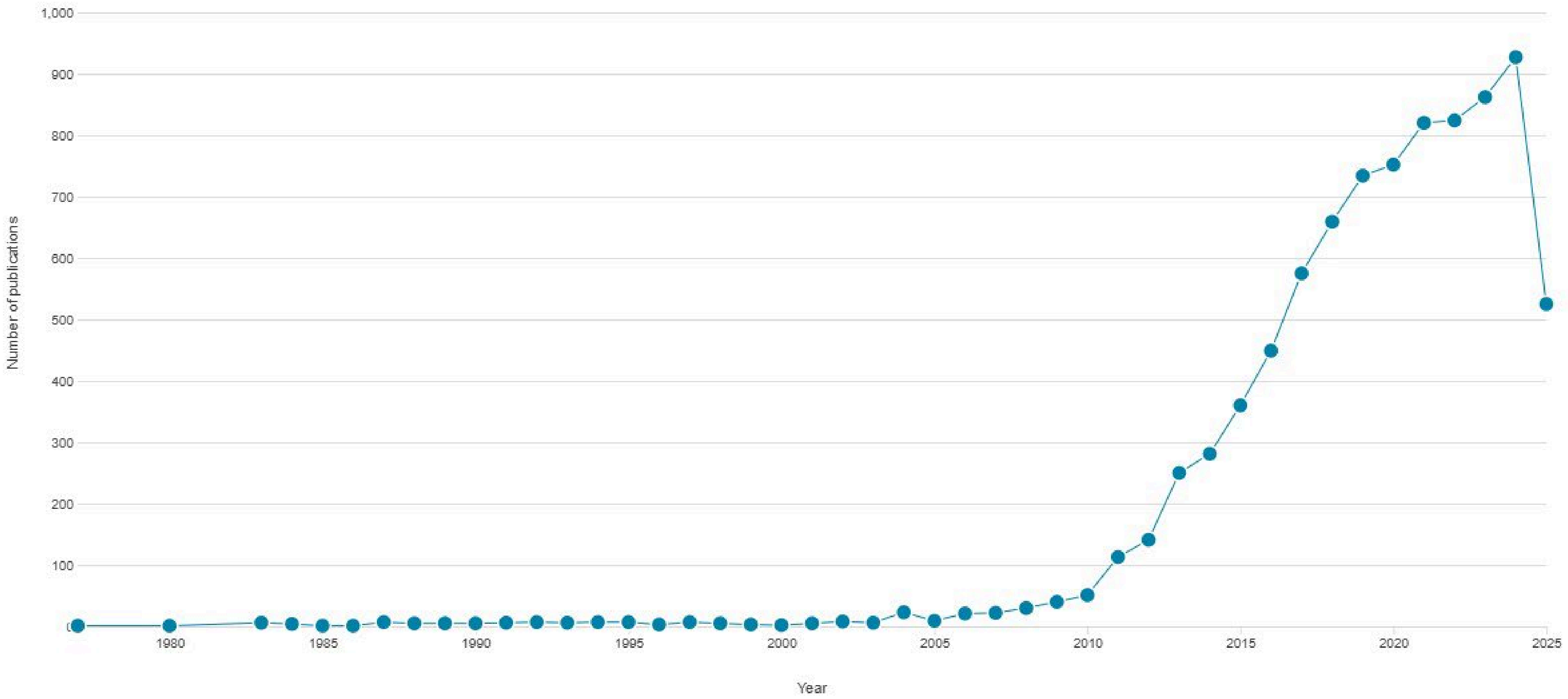
Commercial of the Shelf technology

Flow-batteries
Europe actors



Flow-batteries

Publications



Document Set: Flow Batteries
Date: June 27, 2025
Source: KATI developed by Fraunhofer INT

Fuel Cell for Hydrogen

Search

Search Query: SPUB=(TAC=((" **Proton Exchange Membrane Fuel Cell** *" OR " **Solid Oxide Fuel Cell** *" OR " **Alkaline Fuel Cell** *" OR " **Phosphoric Acid Fuel Cell** *" OR " **Molten Carbonate Fuel Cell** *" OR " **PEMFC** " OR " **SOFC** " OR " **AFC** " OR " **PAFC** " OR " **MCFC** ") AND " **hydro** *")

AND ALIVE=(YES))

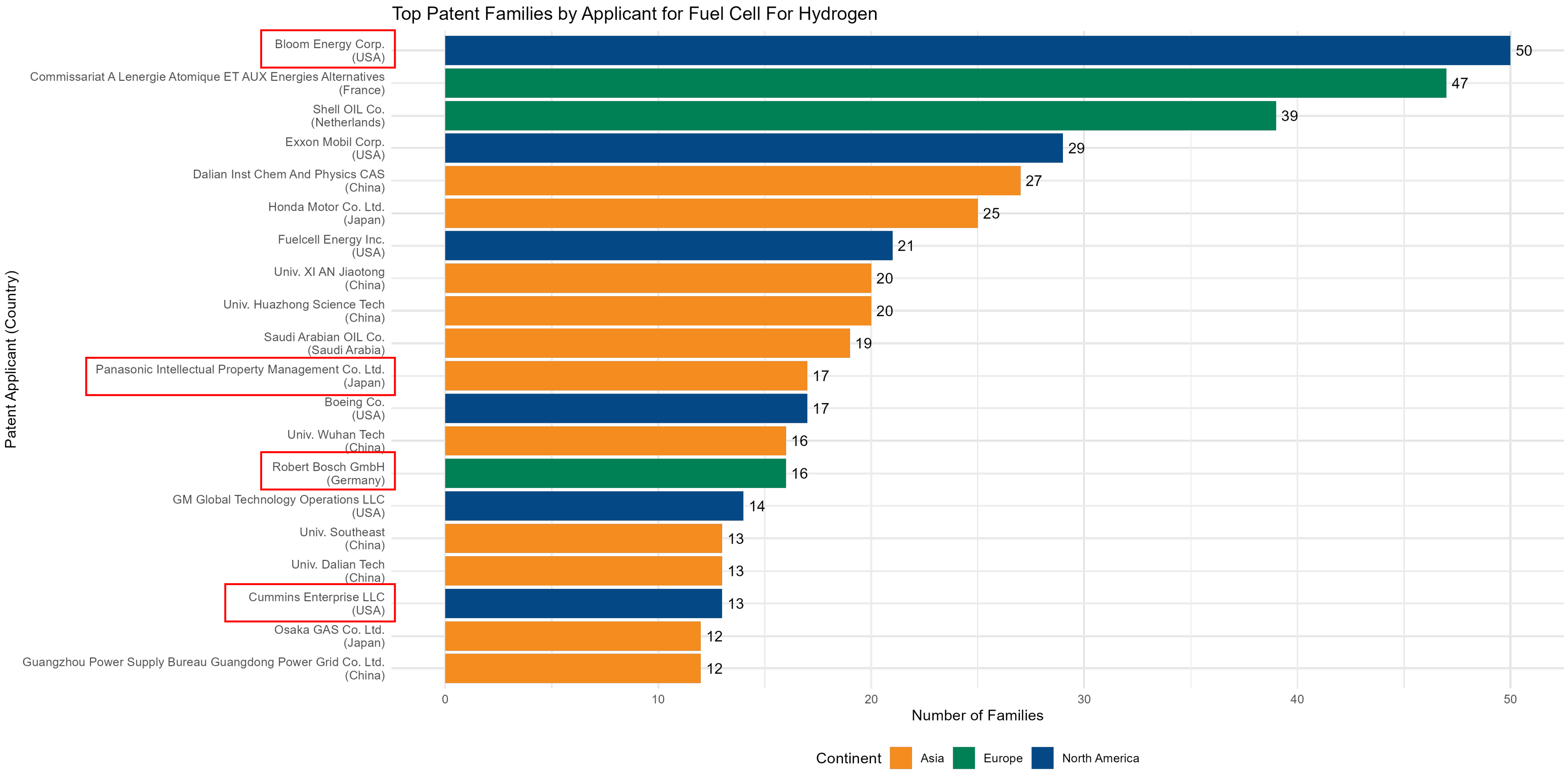
Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 2818

Publications: 19628

Fuel Cell for Hydrogen

World actors

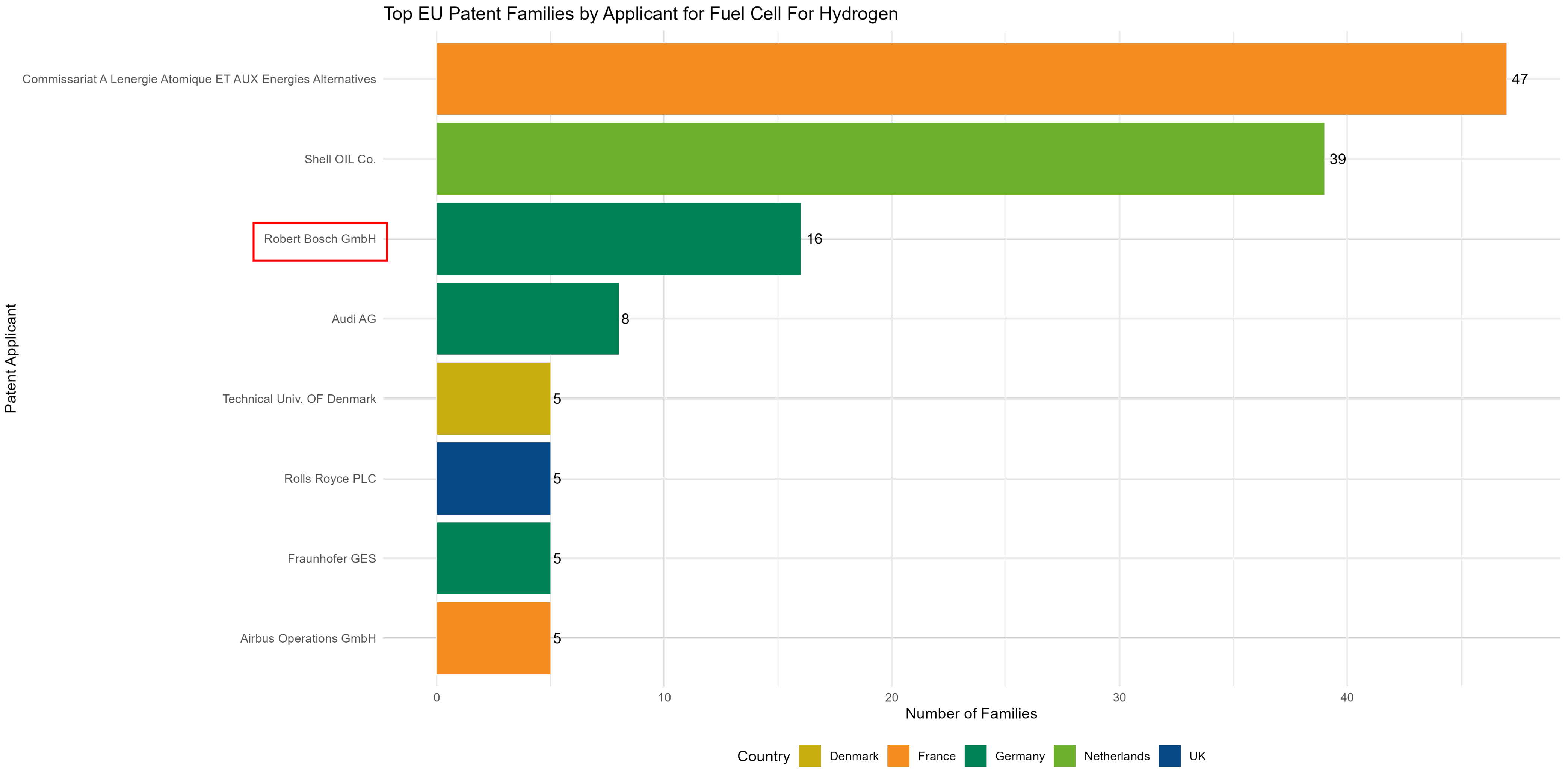


Fraunhofer INT

Commercial of the Shelf technology

Fuel Cell for Hydrogen

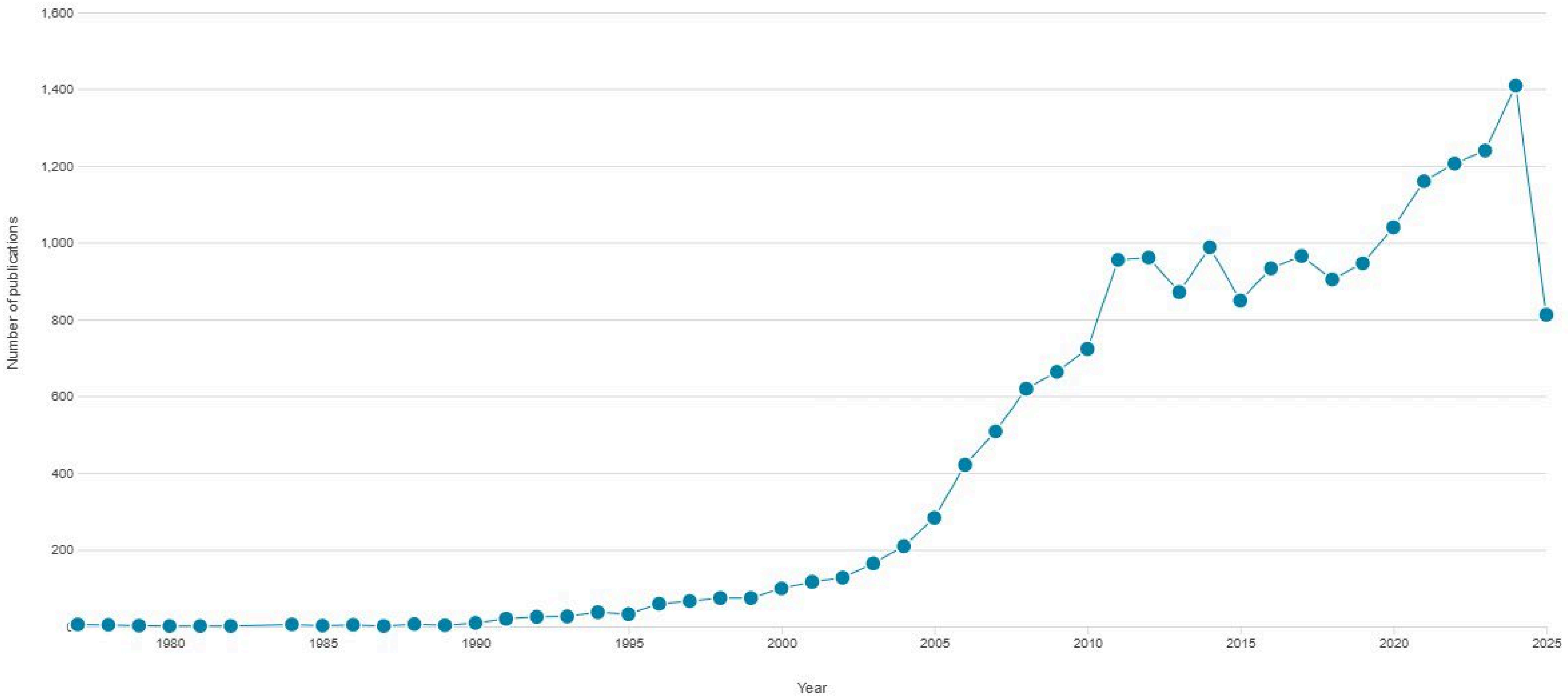
Europe actors



Fraunhofer INT

Fuel Cell for Hydrogen

Publications



Document Set: Fuel cell of hydrogen
Date: July 18, 2025
Source: KATI developed by Fraunhofer INT

Electrolyzers Hydrogen

Search

Search Query: SPUB=(TAC=("**Proton Exchange Membrane Electrolyz***" OR "**Anion Exchange Membrane Electrolyz***" OR "**Proton Exchange Membrane Electrolys***" OR "**Anion Exchange Membrane Electrolys***" OR "**Solid Oxide Electrolysis Cell***" OR "**Alkaline Electrolyz***" OR (("**electrolyz***" OR "**electrolys***") AND (**PEM** OR **AEM**)) AND "**hydrogen***")

AND ALIVE=(YES))

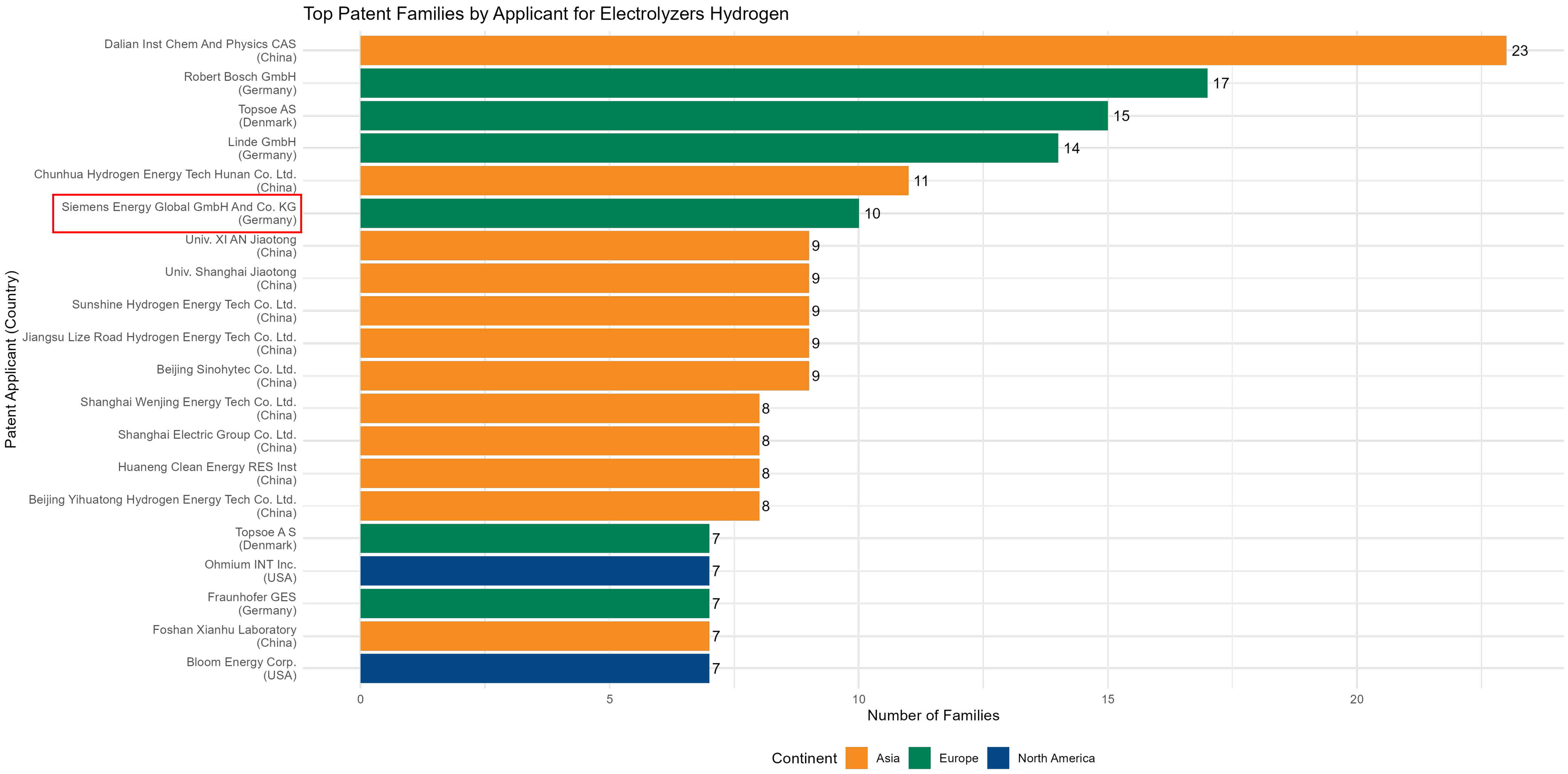
Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 1322

Publications: 6633

Electrolyzers Hydrogen

World actors



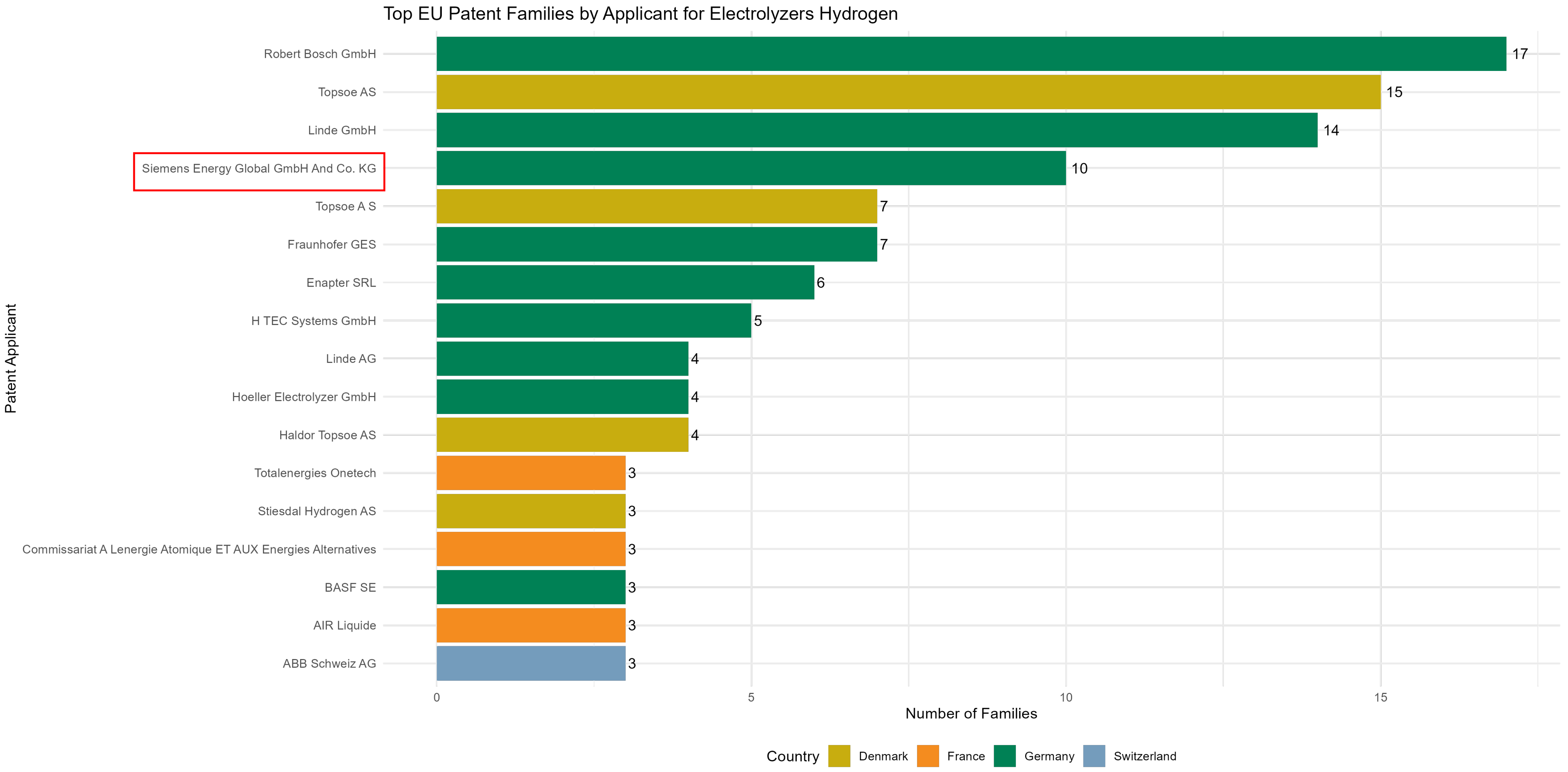
Commercial of the Shelf technology

Electrolyzers Hydrogen

Europe actors

Weitere:

Air Liquide (France): 3

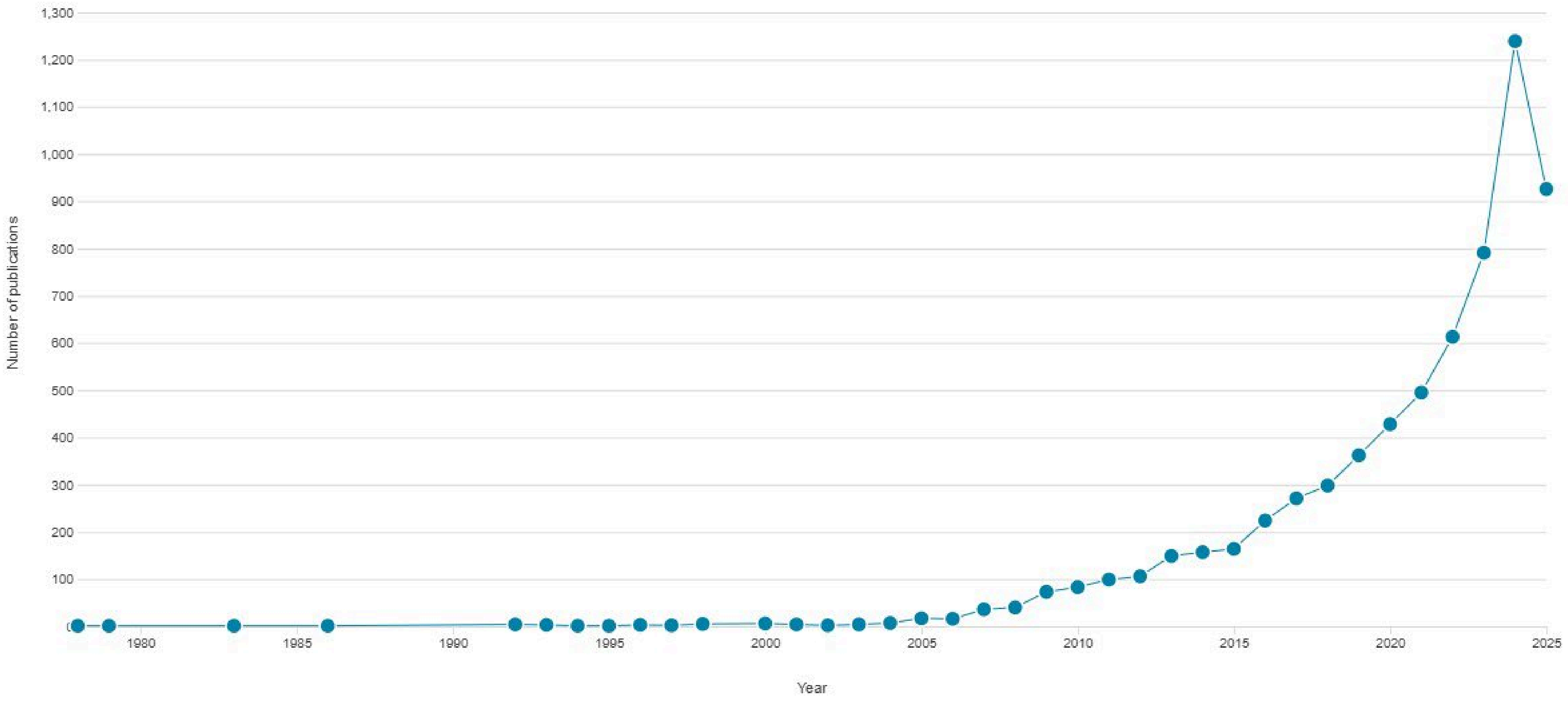


Fraunhofer INT

Commercial of the Shelf technology

Electrolyzers Hydrogen

Publications



Document Set: Electrolyzers Hydrogen
Date: July 18, 2025
Source: KATI developed by Fraunhofer INT

Fraunhofer INT

Micro gas turbines

Search

Search Query: SPUB=(TAC=(**Micro Gas Turbine*** OR (**microturbine*** AND **gas***) OR ("**combined heat and power**" AND "**turbin***"))

OR (CPC=(**Y02E20/14**) AND TAC=("**gas**" AND "**turbin***"))

AND ALIVE=(YES))

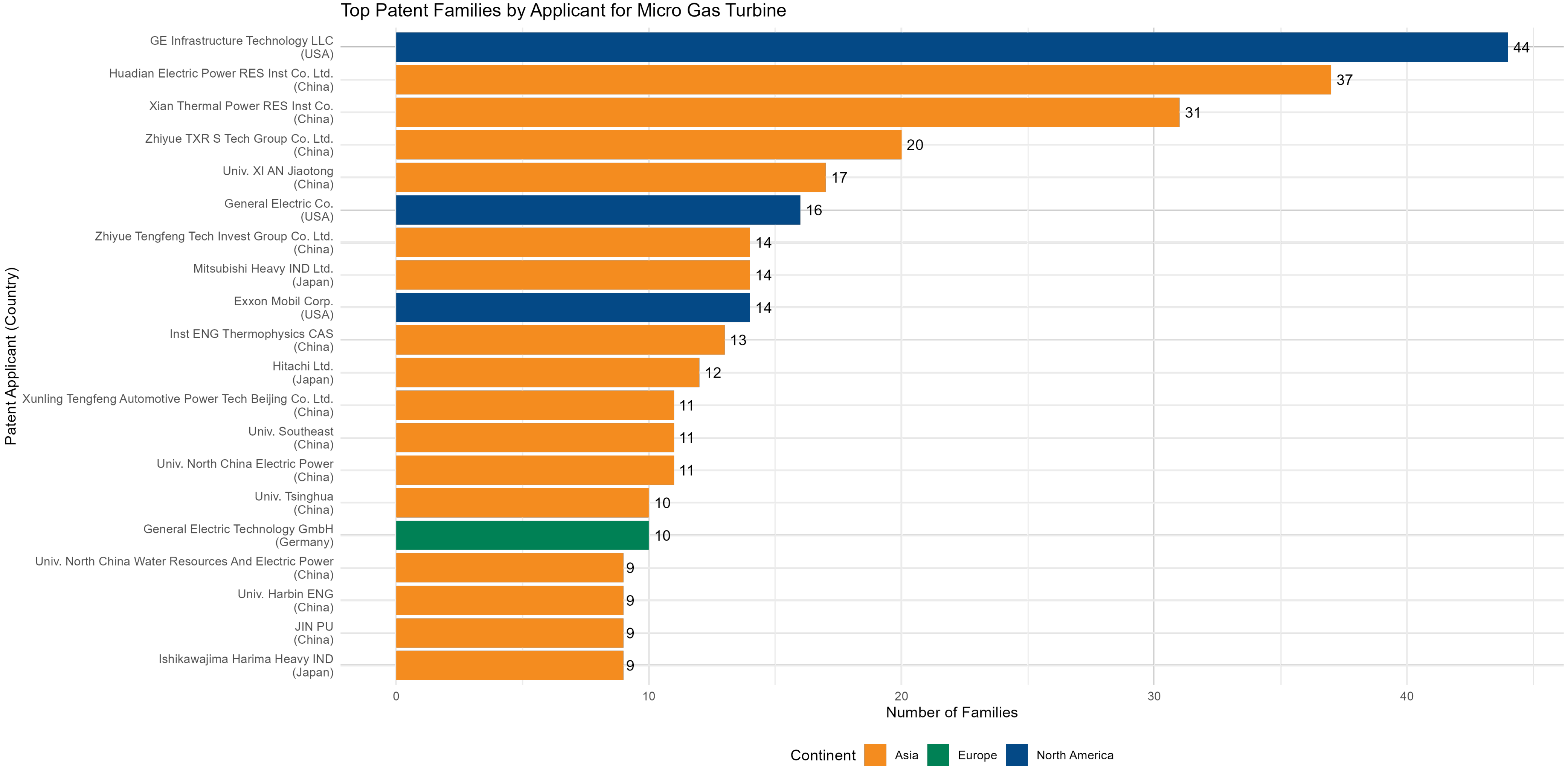
Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 1747

Publications: 3469

Micro gas turbines

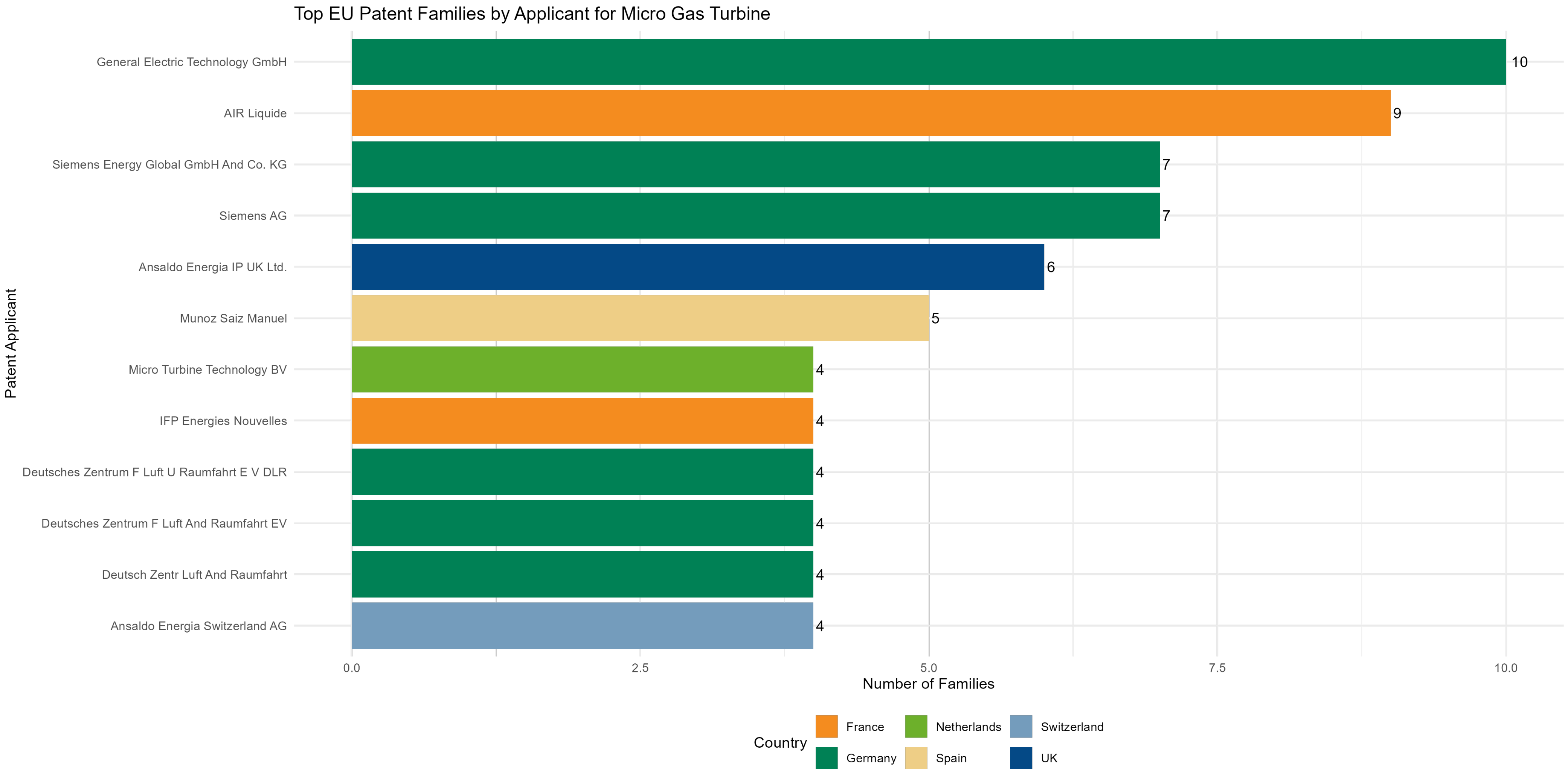
World actors



Fraunhofer INT

Micro gas turbines

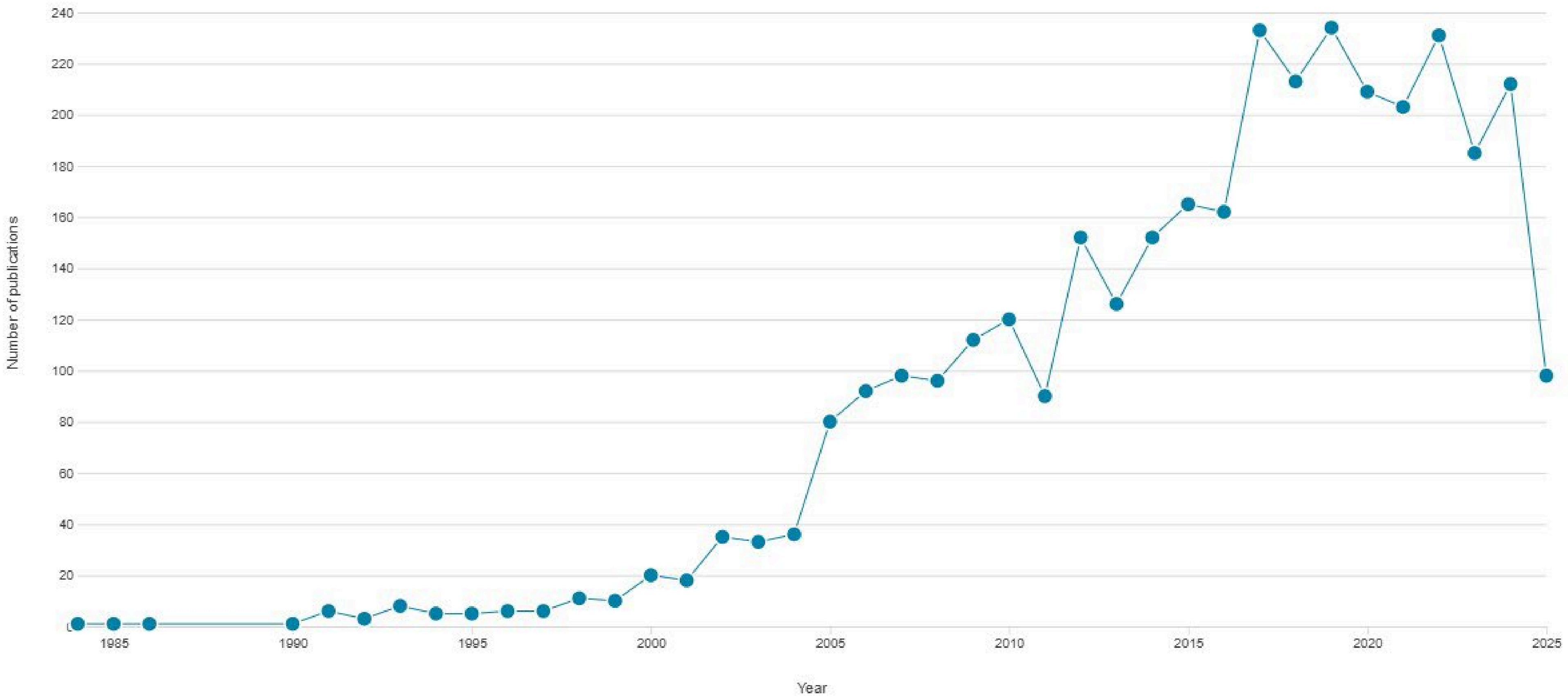
Europe actors



Fraunhofer INT

Commercial of the Shelf technology

Micro gas turbines
Publications



Document Set: Micro gas turbines
Date: July 18, 2025
Source: KATI developed by Fraunhofer INT

Fraunhofer INT

Commercial of the Shelf technology

Biomass and waste-to-energy

Search

Search Query: SPUB=(TAC=(("**Anaerobic Digestion**" OR "**Gasification**" OR "**Pyrolysis**" OR "**Combustion**" OR "**Bubbling Fluidized Bed**" OR "**Hydrothermal Liquefaction**") AND ("**waste to energy**" OR "**biomass**" OR "**biogas**"))

OR CPC=(**Y02E50/10**) OR CPC=(**Y02E50/30**)

AND ALIVE=(YES))

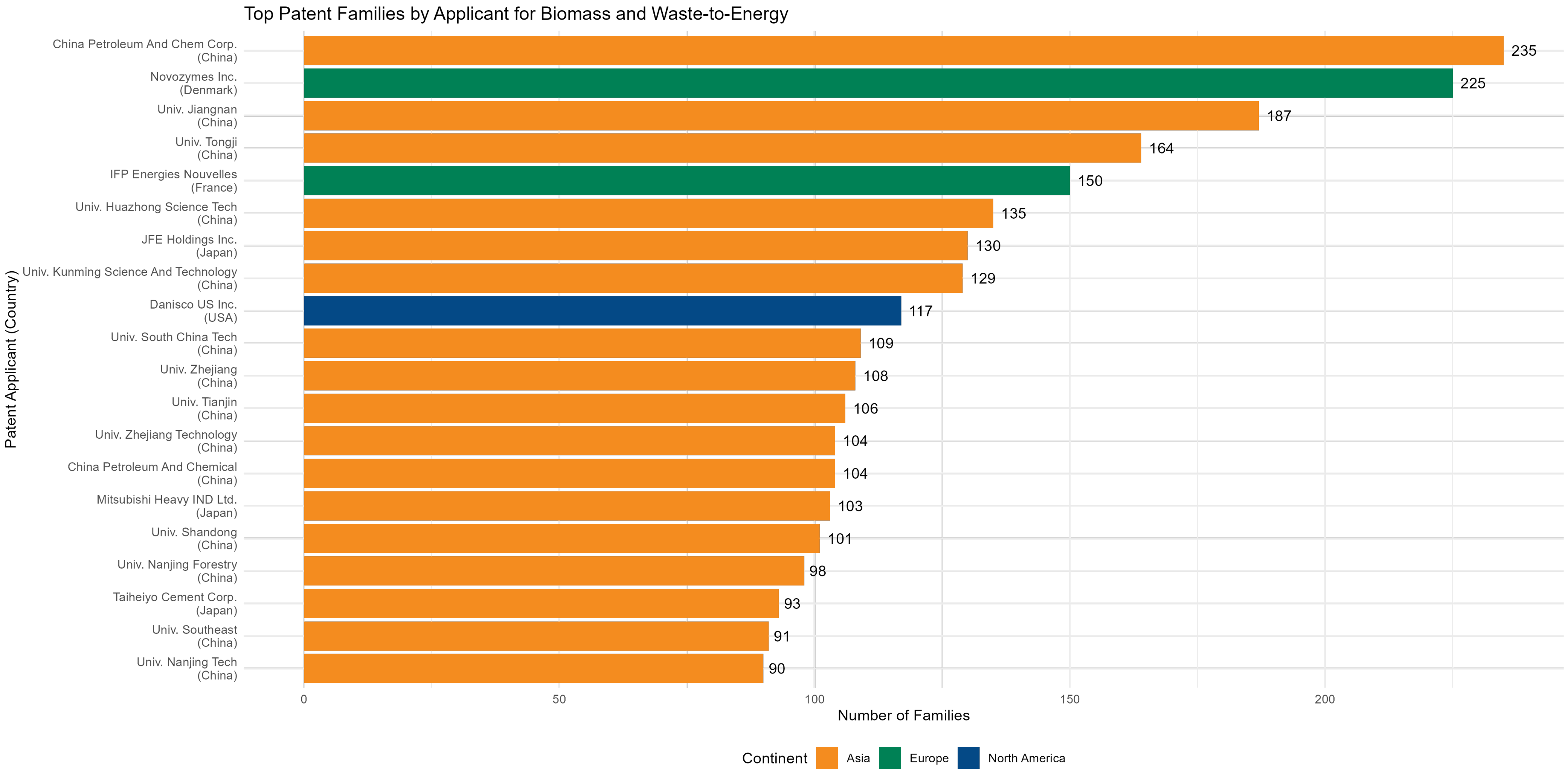
Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 48303

Publications: 93985

Biomass and waste-to-energy

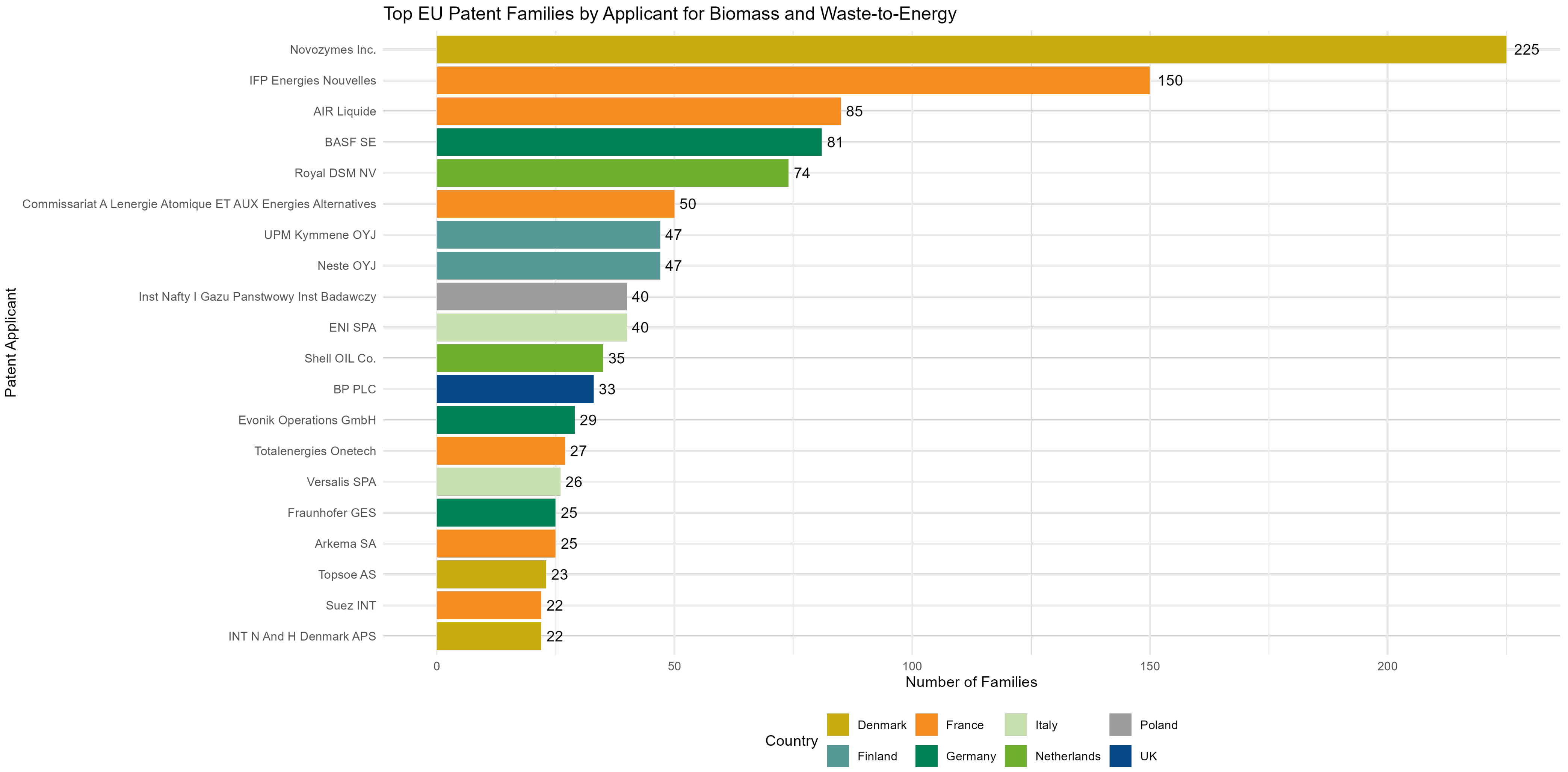
World actors



Fraunhofer INT

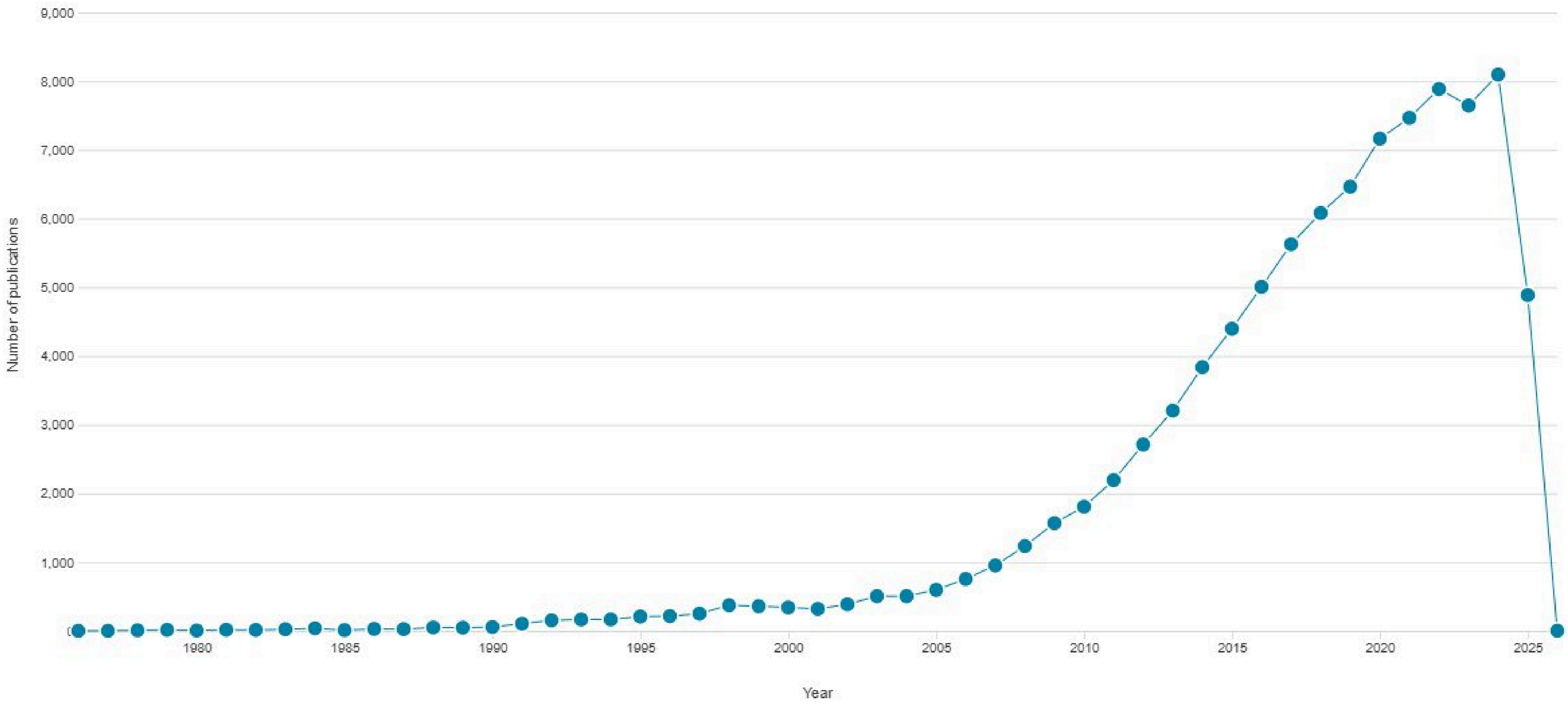
Biomass and waste-to-energy

Europe actors



Fraunhofer INT

Biomass and waste-to-energy
Publications



Document Set: Biomass and waste-to-energy
Date: July 18, 2025
Source: KATI developed by Fraunhofer INT

Wave energy converters
Search

Search Query: SPUB=(IC8=(**F03B13/14**) OR (CPC=(**Y02E10/30**) AND TAC="**wave*** ")

AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

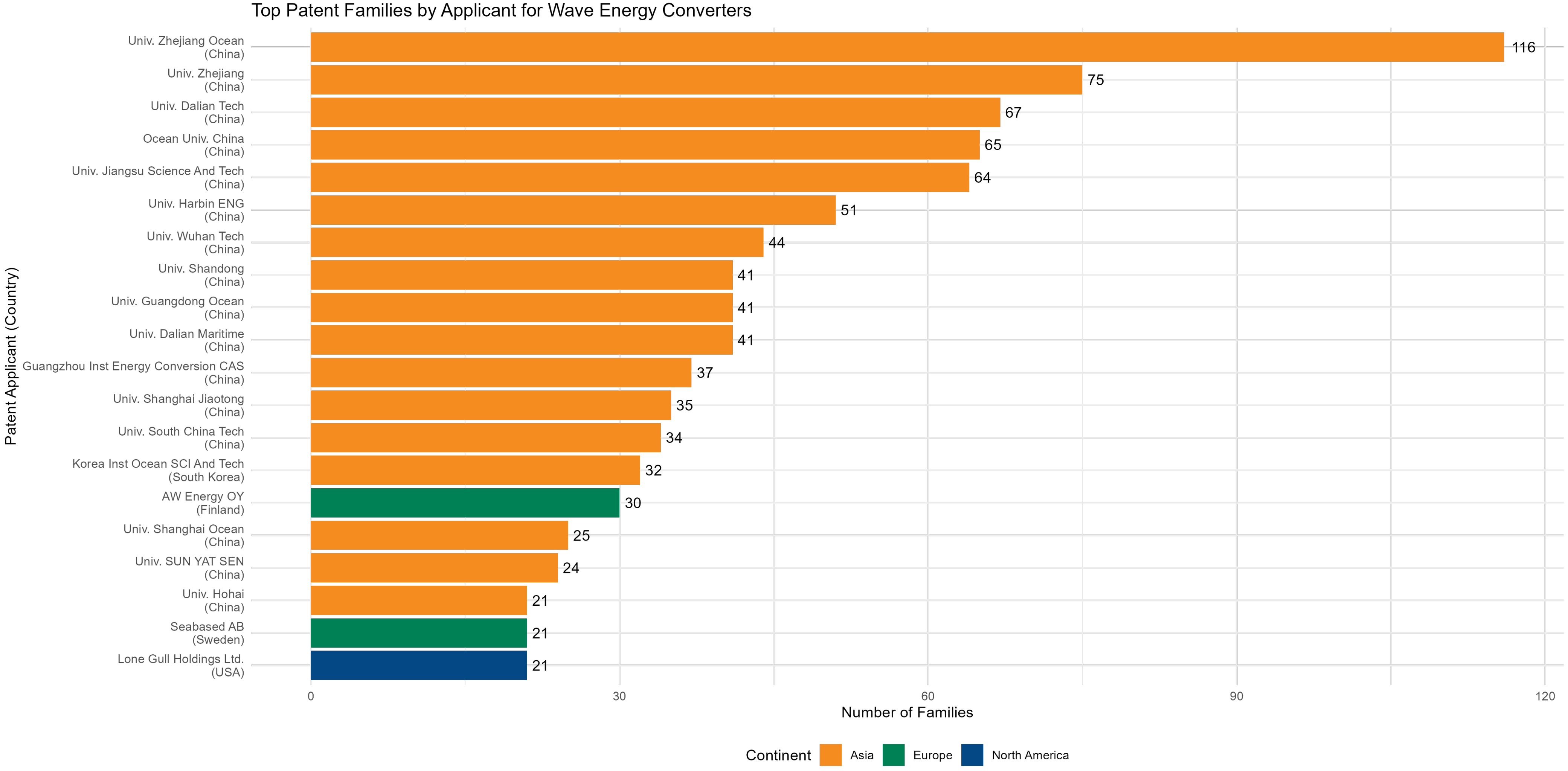
Patentfamilies: 5707

Publications: 5329

Emerging highly promising technology

Wave energy converters

World actors

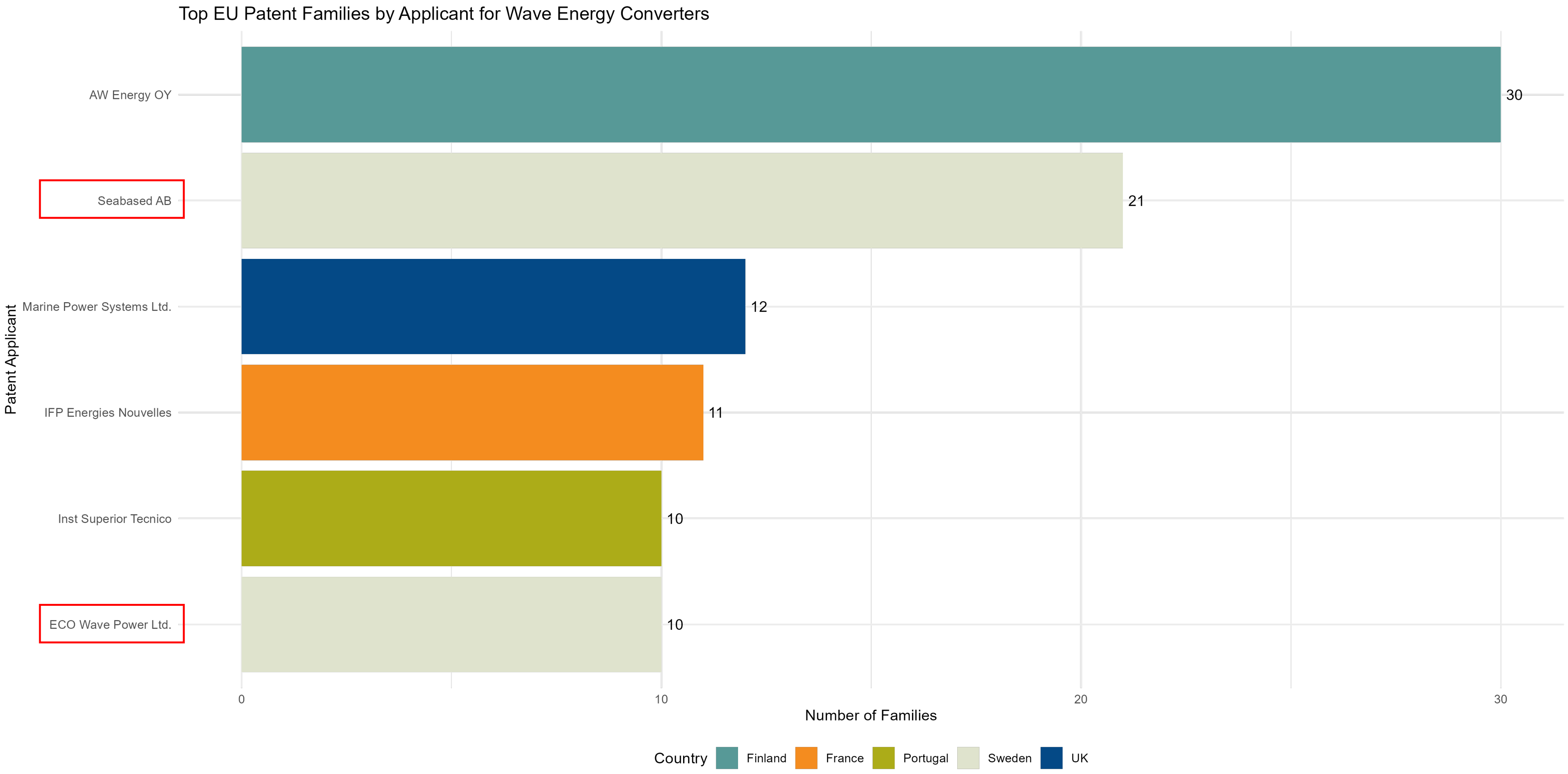


Fraunhofer INT

Emerging highly promising technology

Wave energy converters

Europe actors

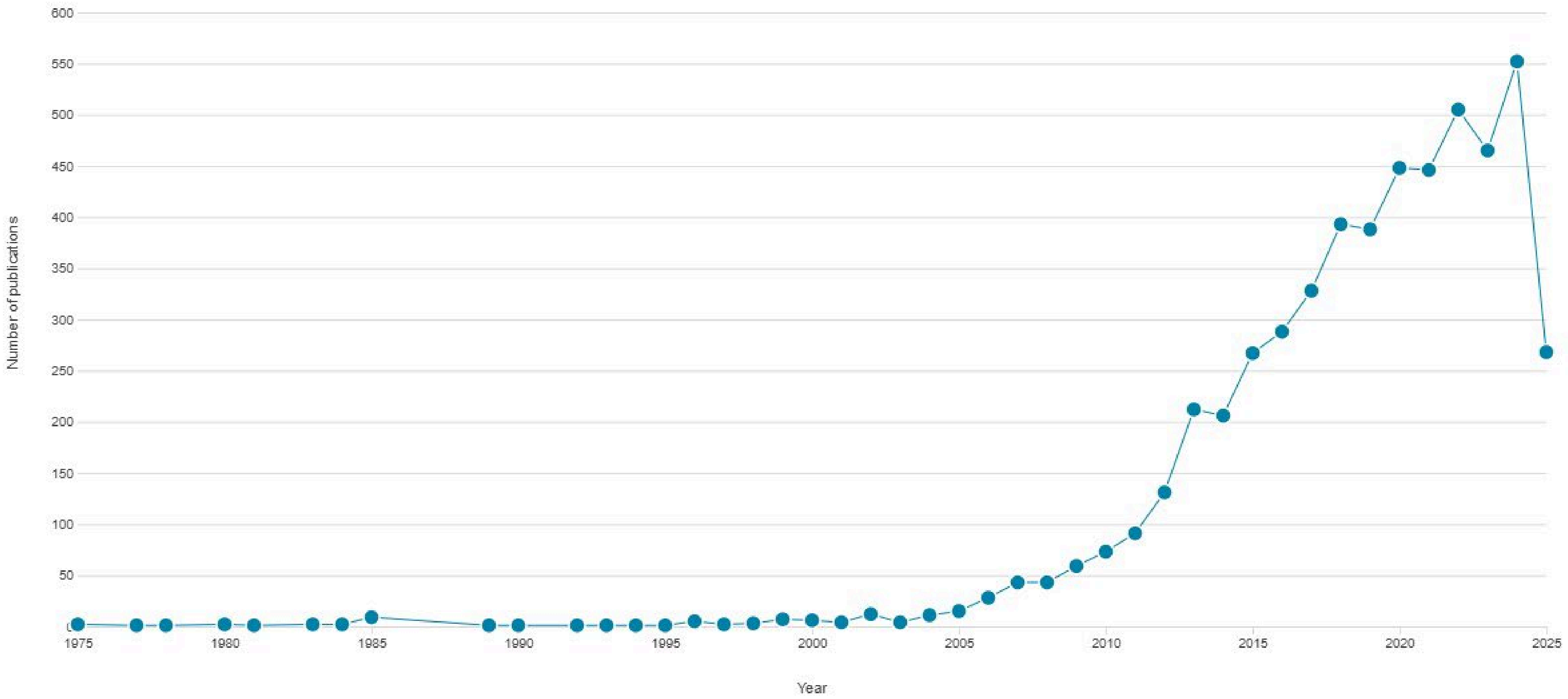


Fraunhofer INT

Emerging highly promising technology

Wave energy converters

Publications



Document Set: Wave energy converters
Date: July 18, 2025
Source: KATI developed by Fraunhofer INT

Sodium-Ion Batteries

Search

Search Query: SPUB=(TAC=("**sodium-ion batter***" OR "**na-ion batter***")

AND ALIVE=(YES))

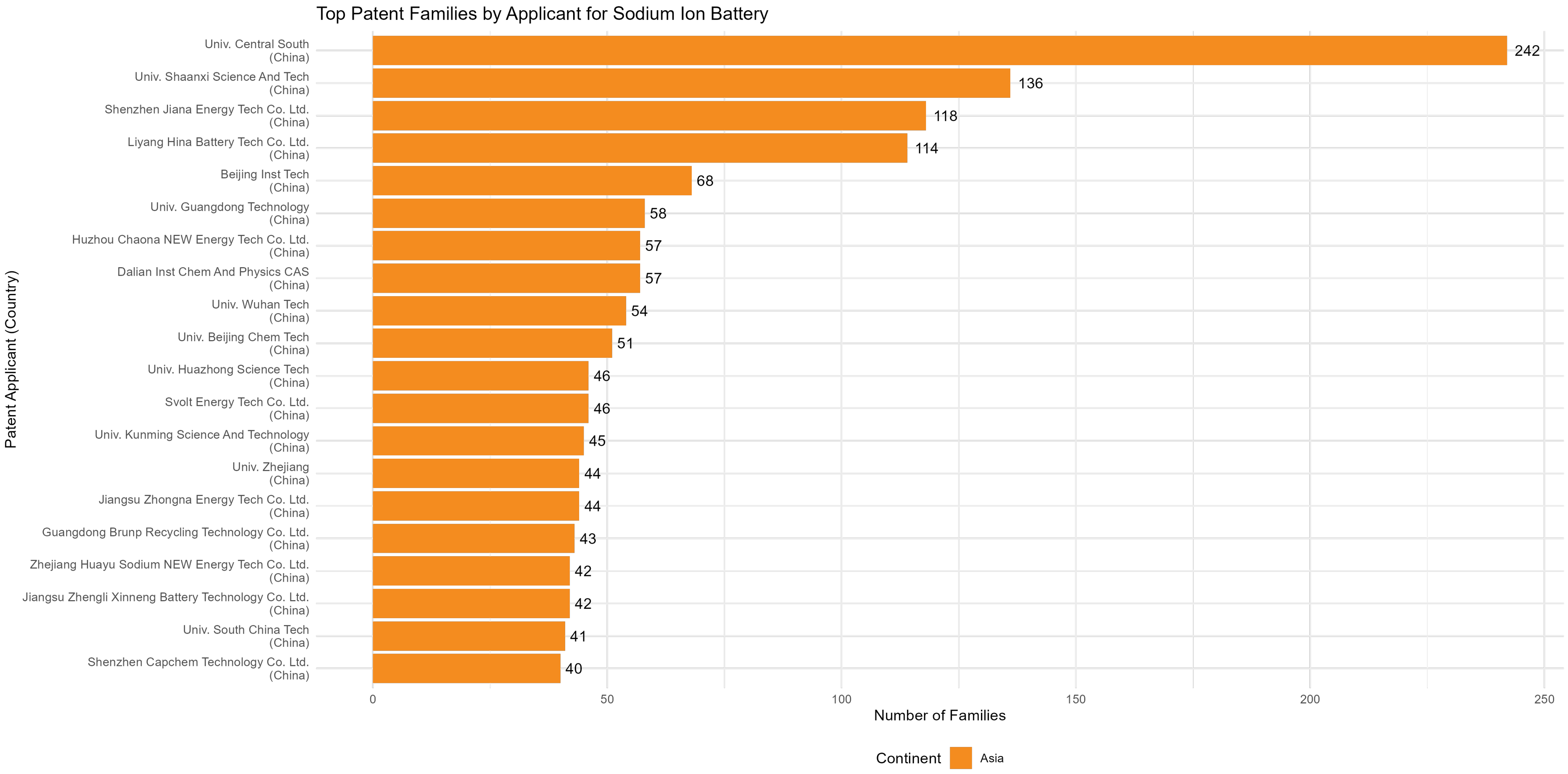
Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 9060

Publications: 19090

Sodium-Ion Batteries

World actors



 15.09.2025

Fraunhofer INT

Emerging highly promising technology

Sodium-Ion Batteries

Europe actors

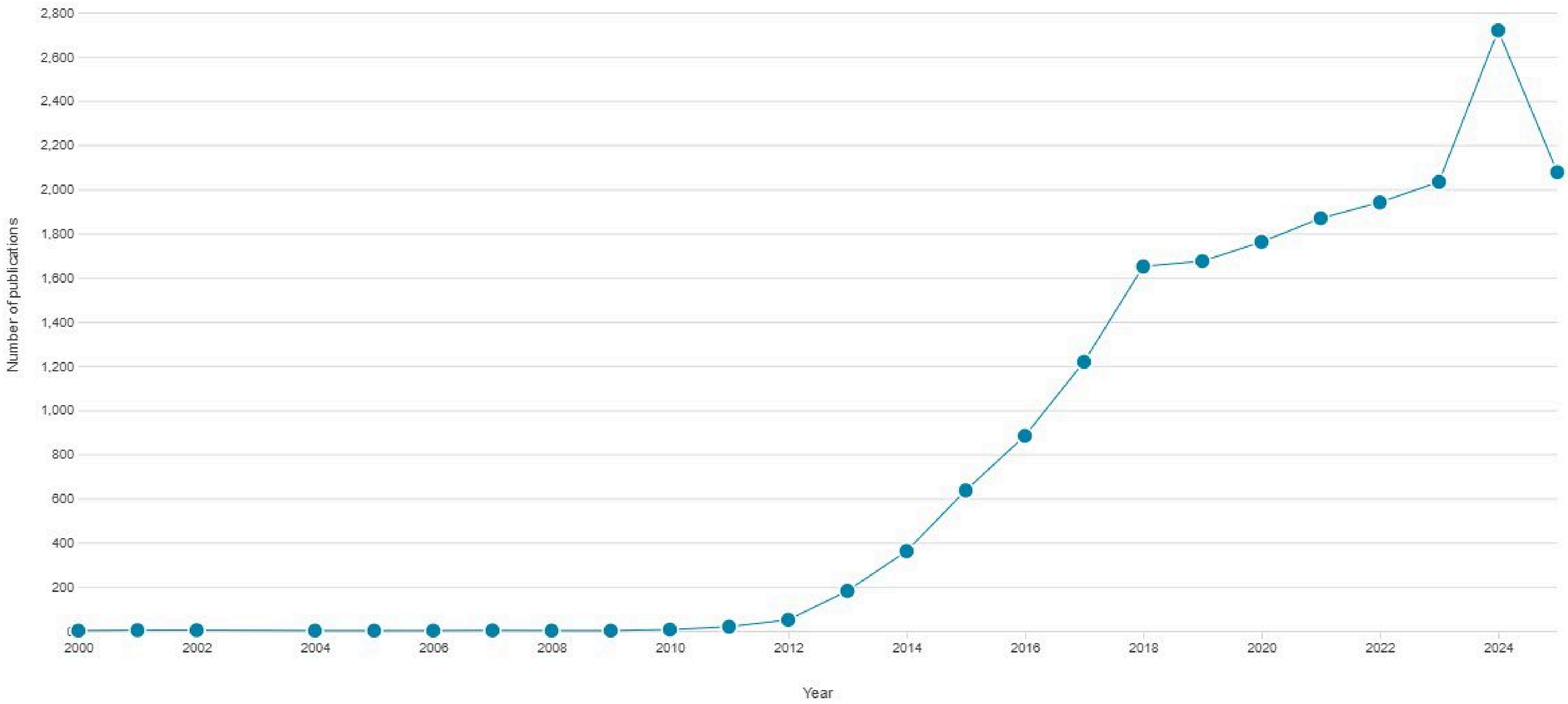
Nicht vorhanden in den Top 100 Applicants!

Fraunhofer INT

Emerging highly promising technology

Sodium-Ion Batteries

Publications



Document Set: Sodium-Ion Batteries
Date: July 18, 2025
Source: KATI developed by Fraunhofer INT

Emerging highly promising technology

Metal Hydrides of Hydrogen Storage

Search

Search Query: SPUB=(TAC=("**metal hydrid***" AND "**hydrogen stor***")

AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

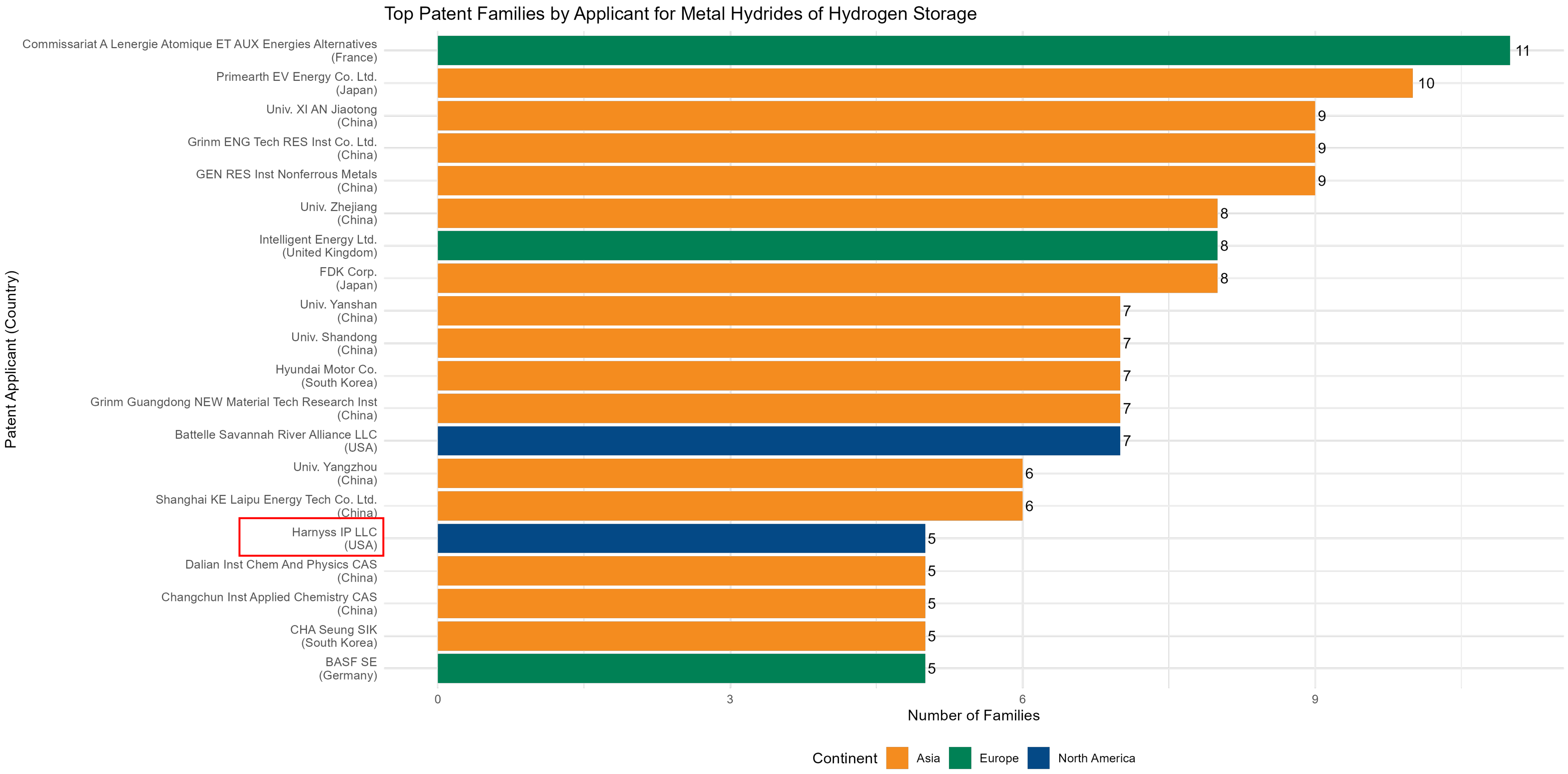
Patentfamilies: 624

Publications: 4823

Fraunhofer INT

Metal Hydrides of Hydrogen Storage

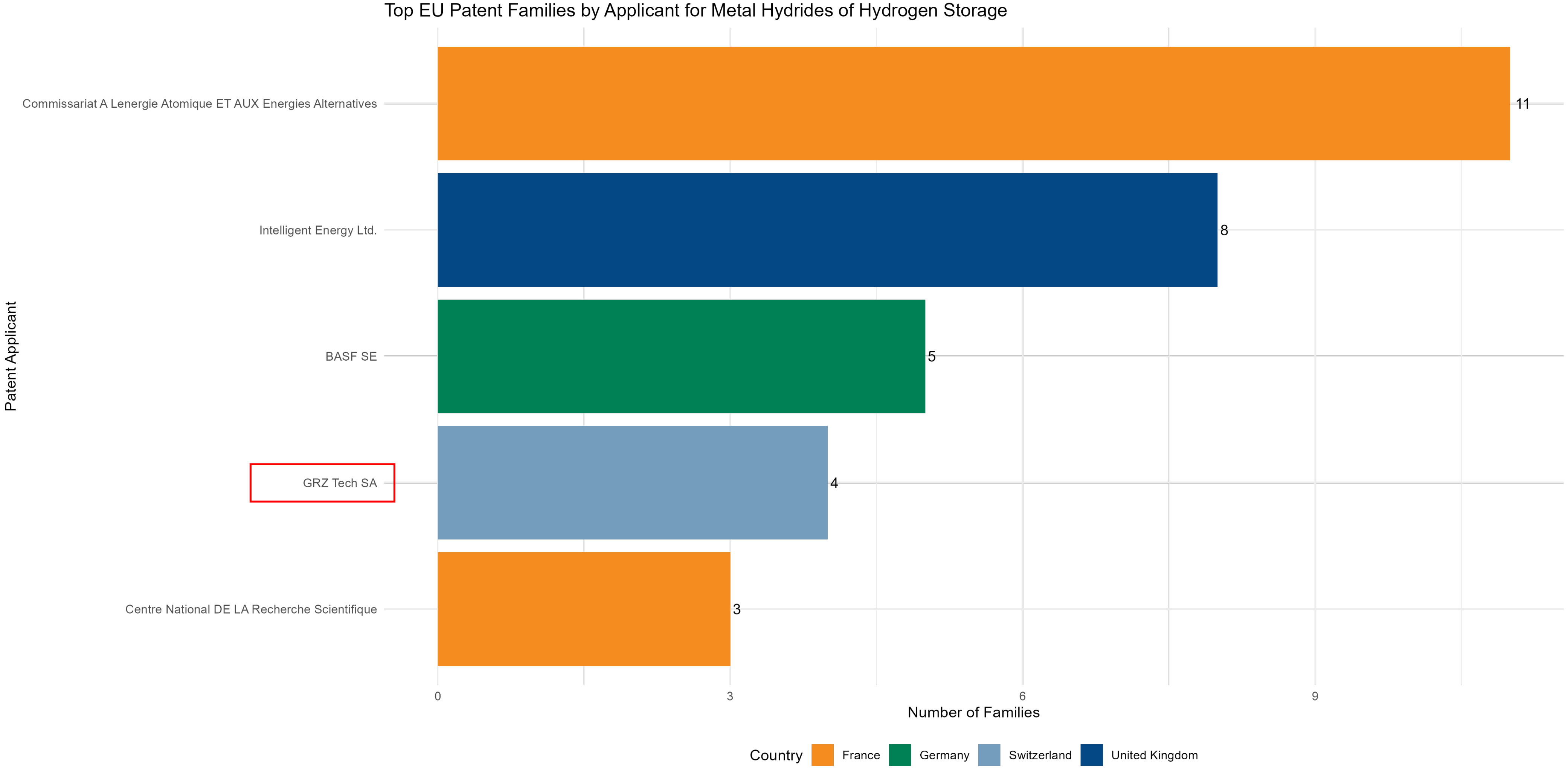
World actors



Fraunhofer INT

Metal Hydrides of Hydrogen Storage

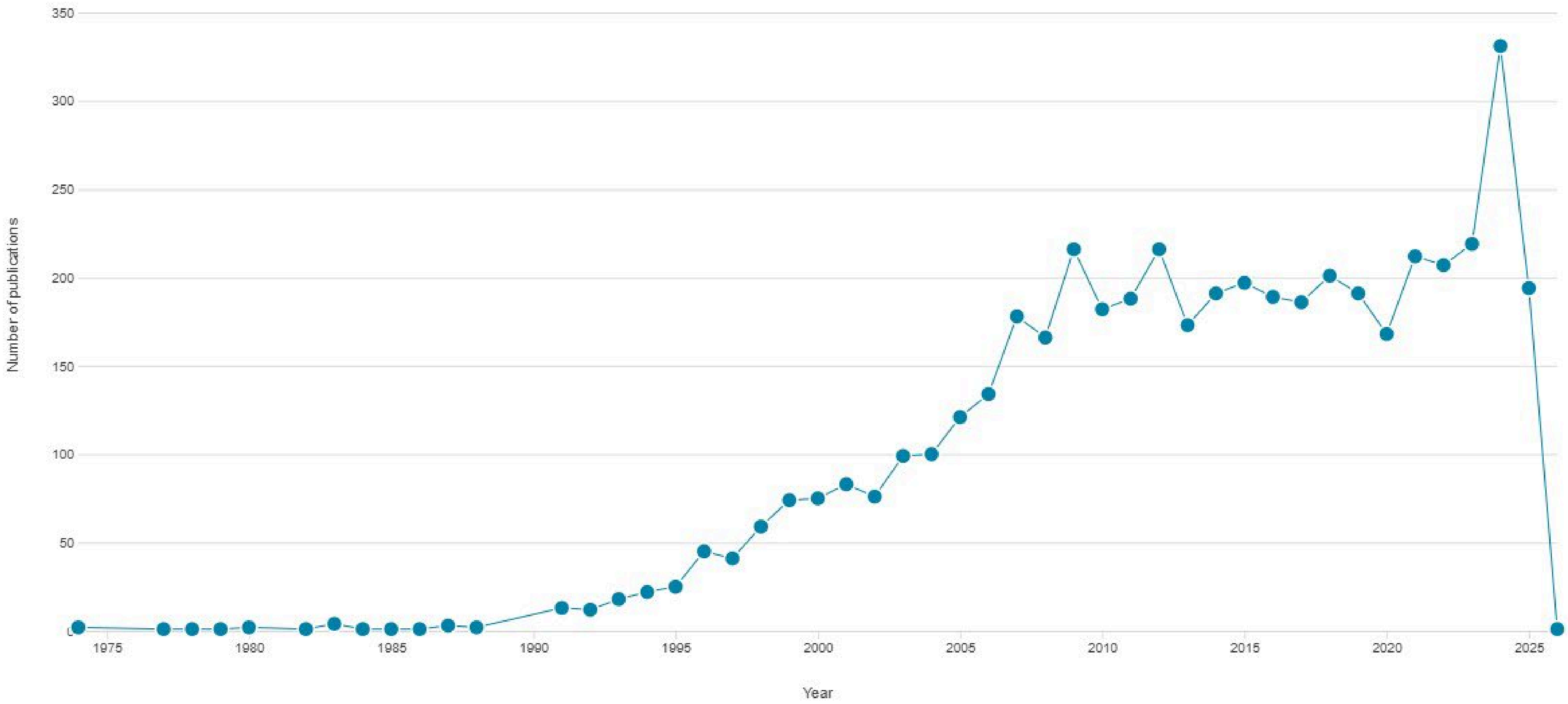
Europe actors



Emerging highly promising technology

Metal Hydrides of Hydrogen Storage

Publications



Document Set: Metal Hydrides of Hydrogen Storage
Date: July 18, 2025
Source: KATI developed by Fraunhofer INT

Solid-state batteries

Search

Search Query: SPUB=(TAC=("**solid-state batter***" OR (("**Solid Polymer Electrolyte***" OR "**Garnet-Type**" OR "**NASICON-Type**" OR "**Thio-LISICON**" OR "**Sulfide-Based**") AND "**batter***"))

OR IC8=(**H01M10/0562**)

AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 15962

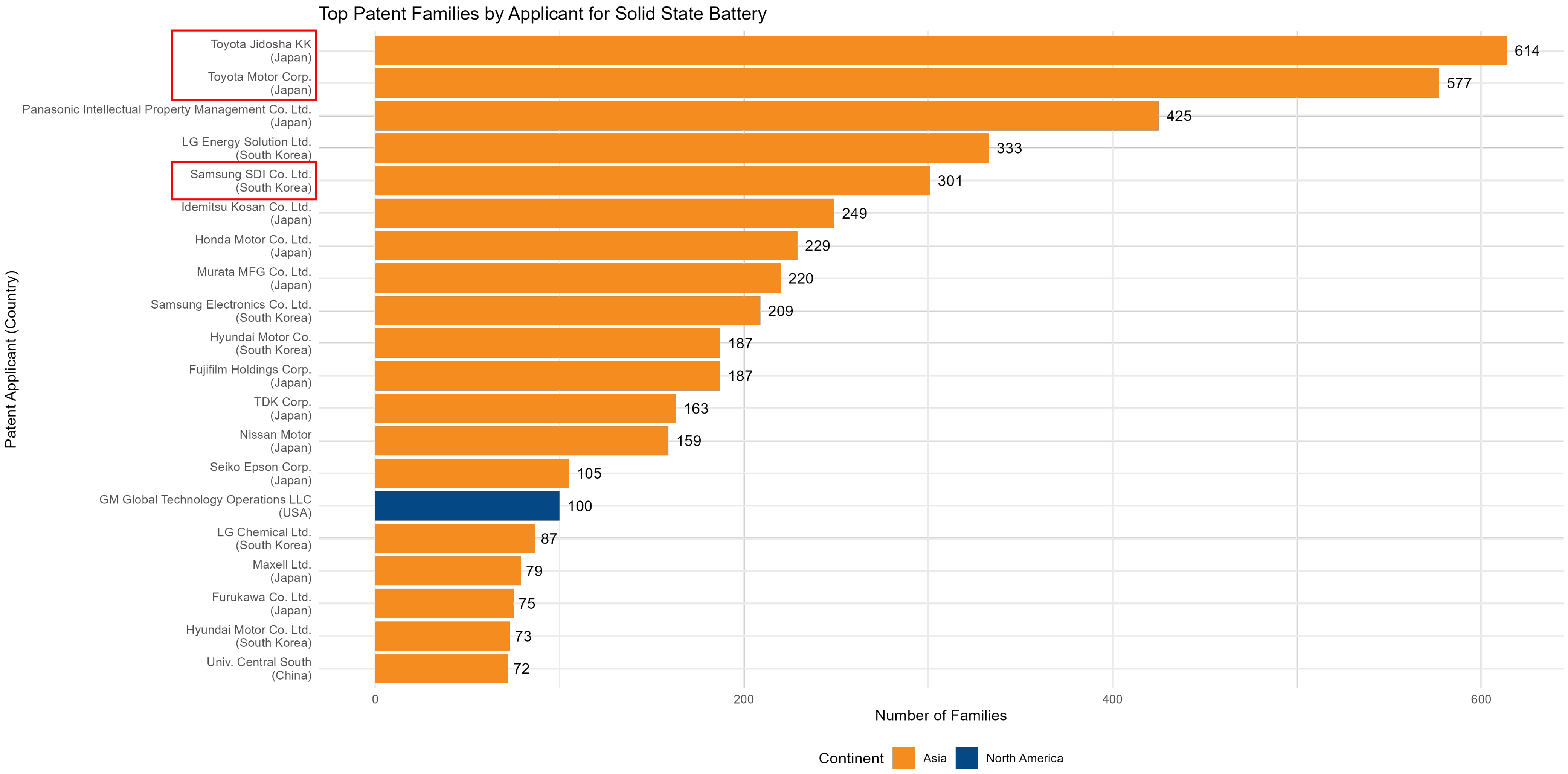
Publications: 12834

Solid-state batteries

World actors

Weitere:

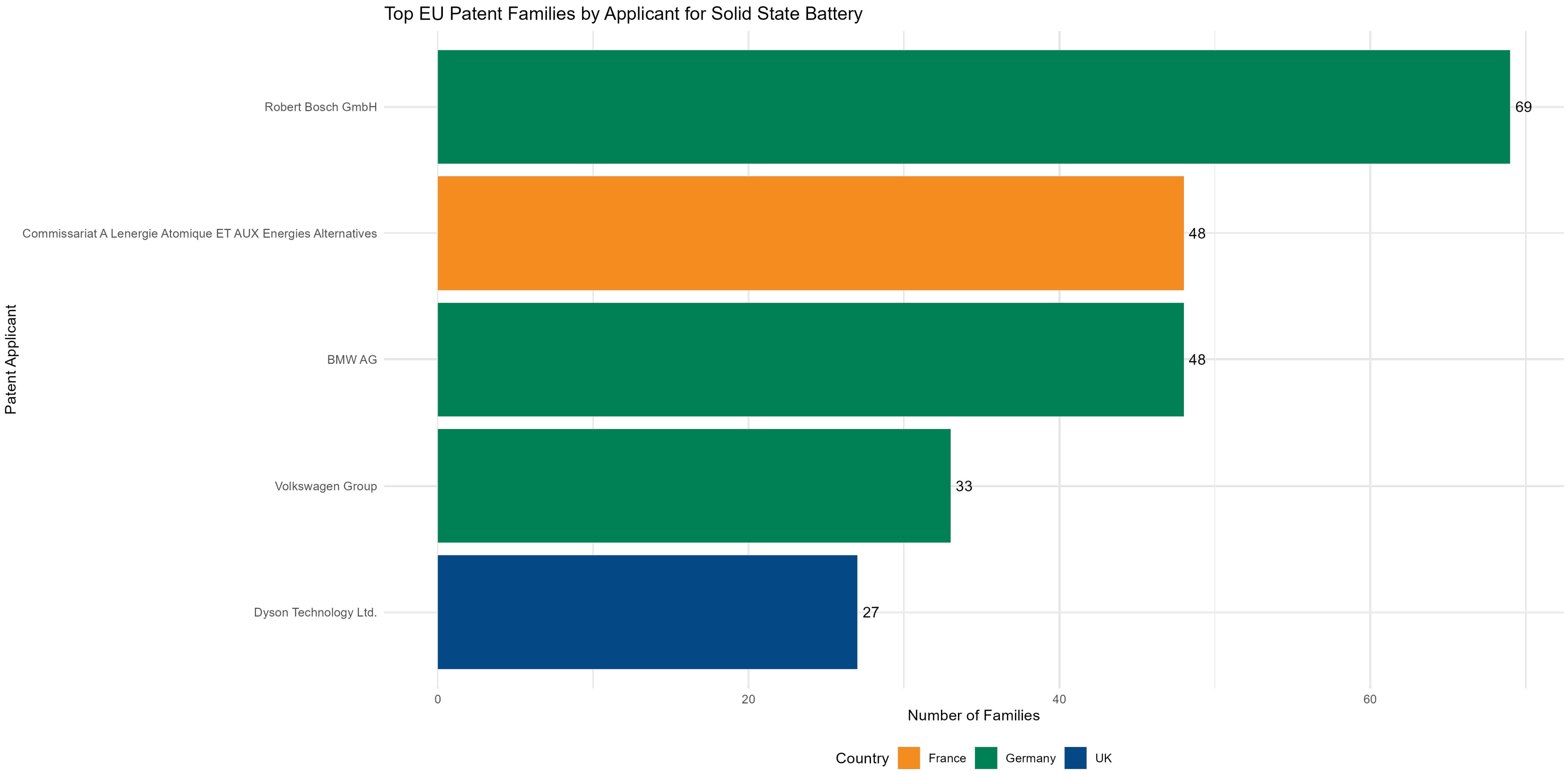
QuantumScape (USA): 45



Fraunhofer INT

Solid-state batteries

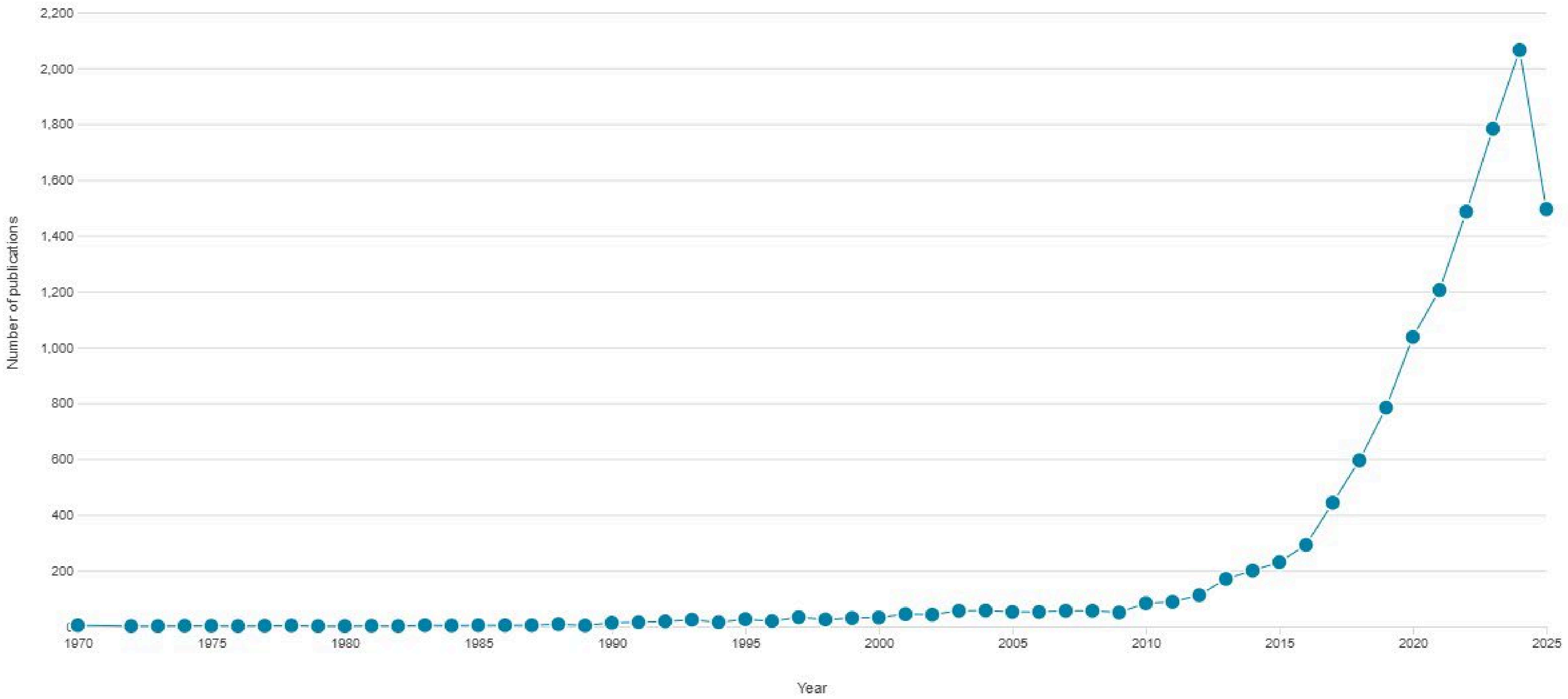
Europe actors



Emerging highly promising technology

Solid-state batteries

Publications



Document Set: Solid-state batteries
Date: July 18, 2025
Source: KATI developed by Fraunhofer INT

Perovskite and tandem solar cell

Search

Search Query: SPUB=(TAC=("**perovskite solar cell***" OR "**tandem solar cell***")

AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

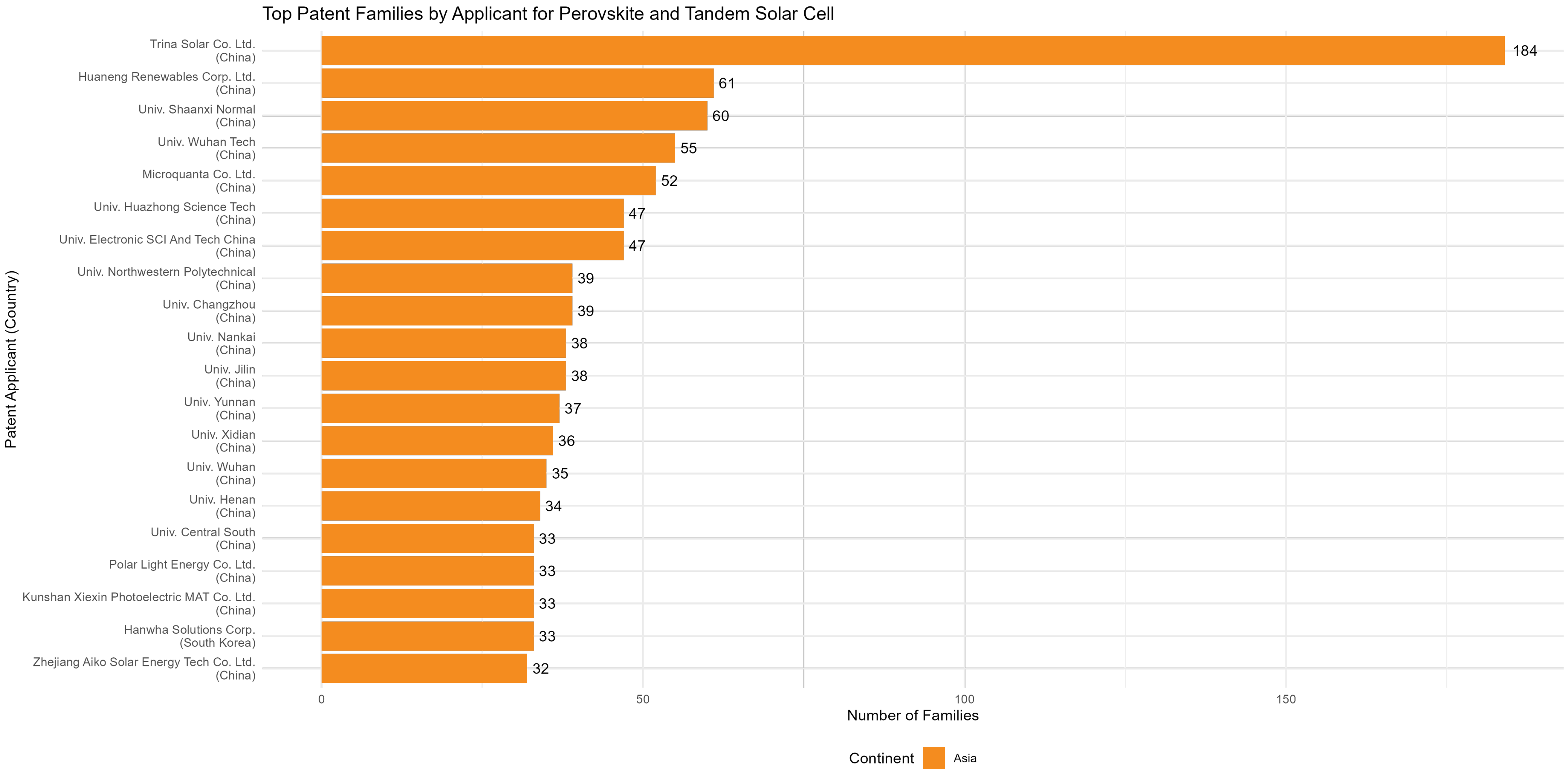
Patentfamilies: 5268

Publications: 33342

Emerging moderately promising technology

Perovskite and tandem solar cell

World actors



Fraunhofer INT

Emerging moderately promising technology

Perovskite and tandem solar cell

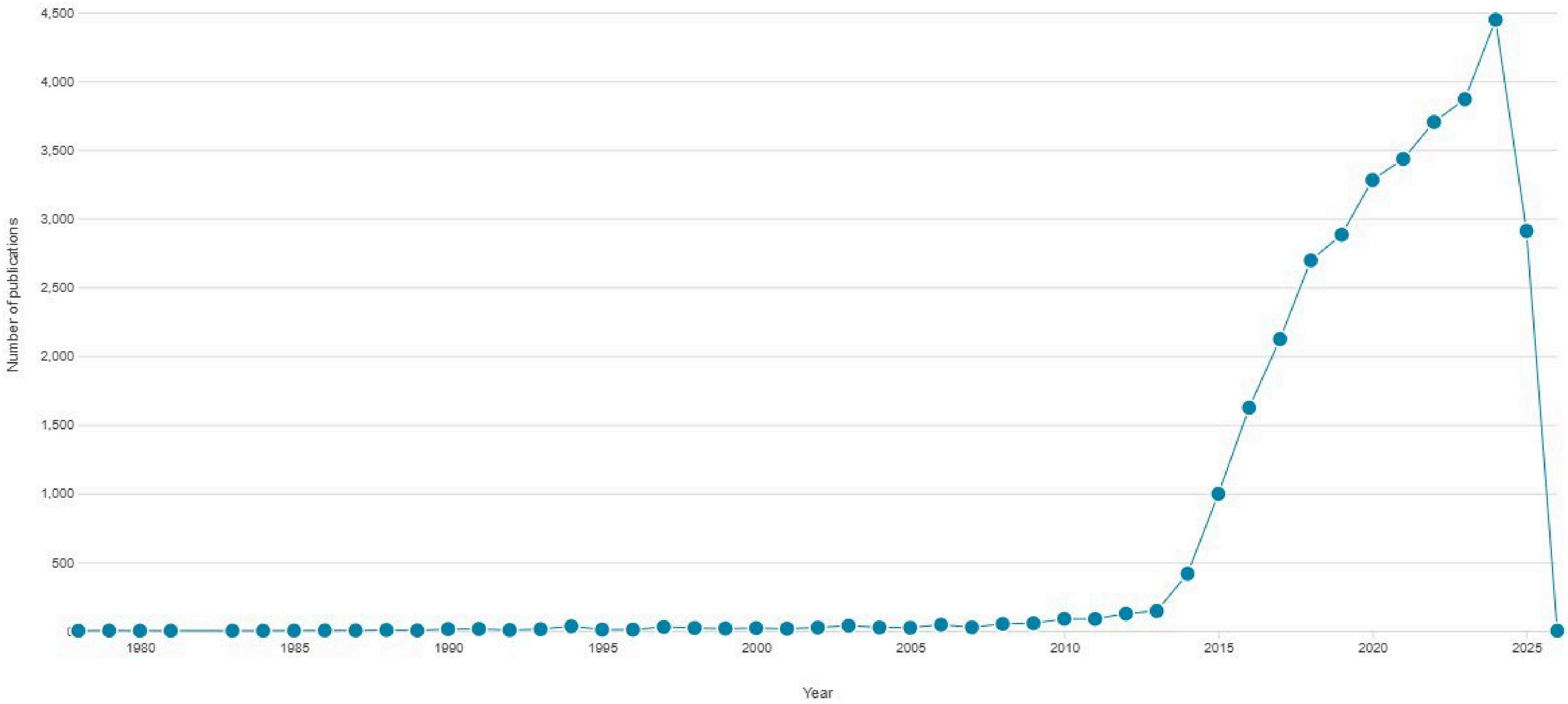
Europe actors

Nicht vorhanden in den Top 125 Applicants!

Emerging moderately promising technology

Perovskite and tandem solar cell

Publications



Document Set: Perovskite and tandem solar cell
Date: July 18, 2025
Source: KATI developed by Fraunhofer INT

Fraunhofer INT

Airborne wind & kites

Search

Search Query: SPUB=(TAC=(("**airborne wind energy**" OR "**tethered wind power**" OR "airborne wind turbine" OR "**tethered flying generator**" OR "**airborne generator**" OR "**flying wind turbine**" OR "**kite-based energy**" OR "**airborne power generation**")

AND (**wind** OR **energy** OR **power**))

AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

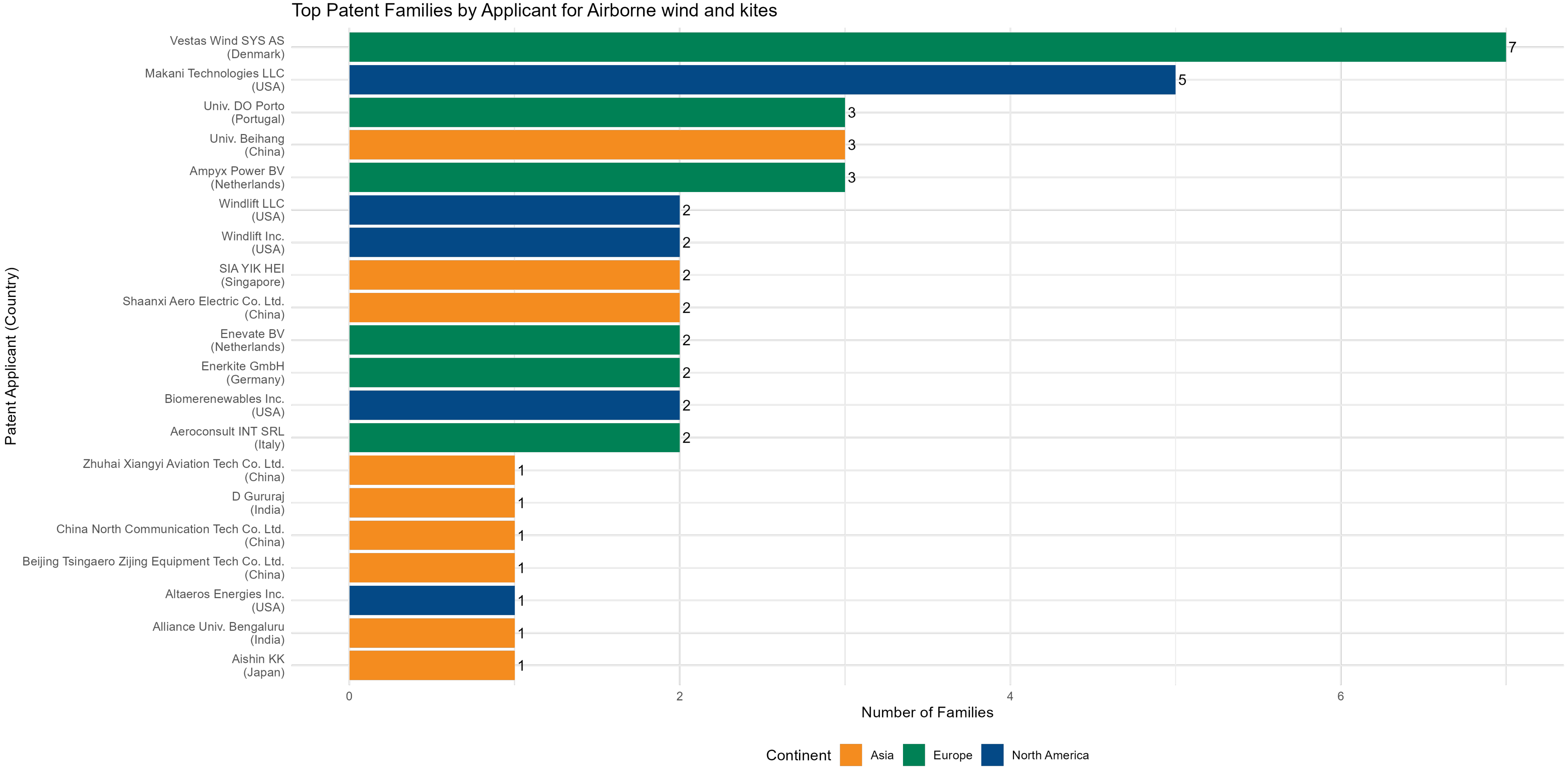
Patentfamilies: 62

Publications: 391

Emerging moderately promising technology

Airborne wind & kites

World actors

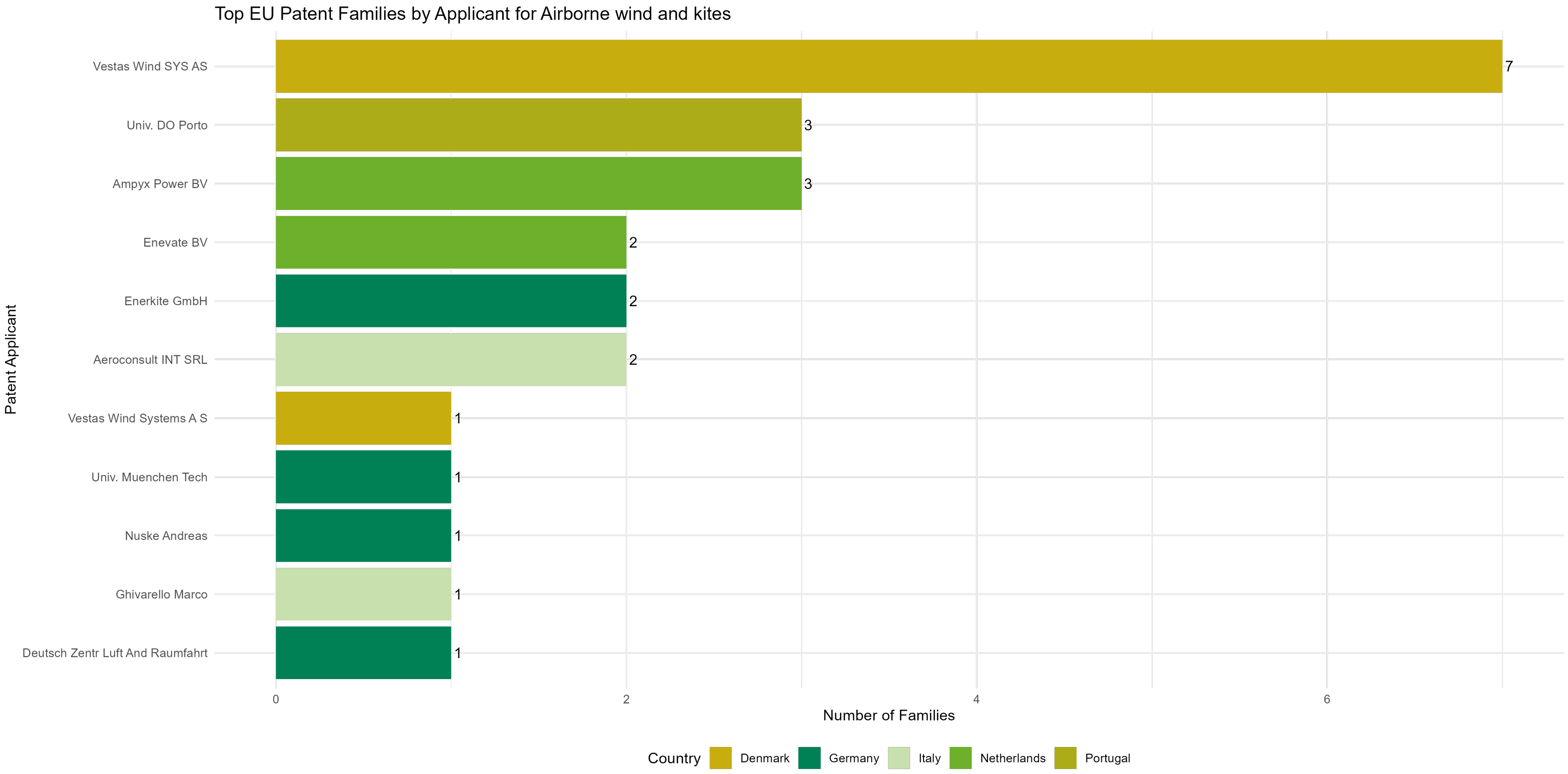


Fraunhofer INT

Emerging moderately promising technology

Airborne wind & kites

Europe actors

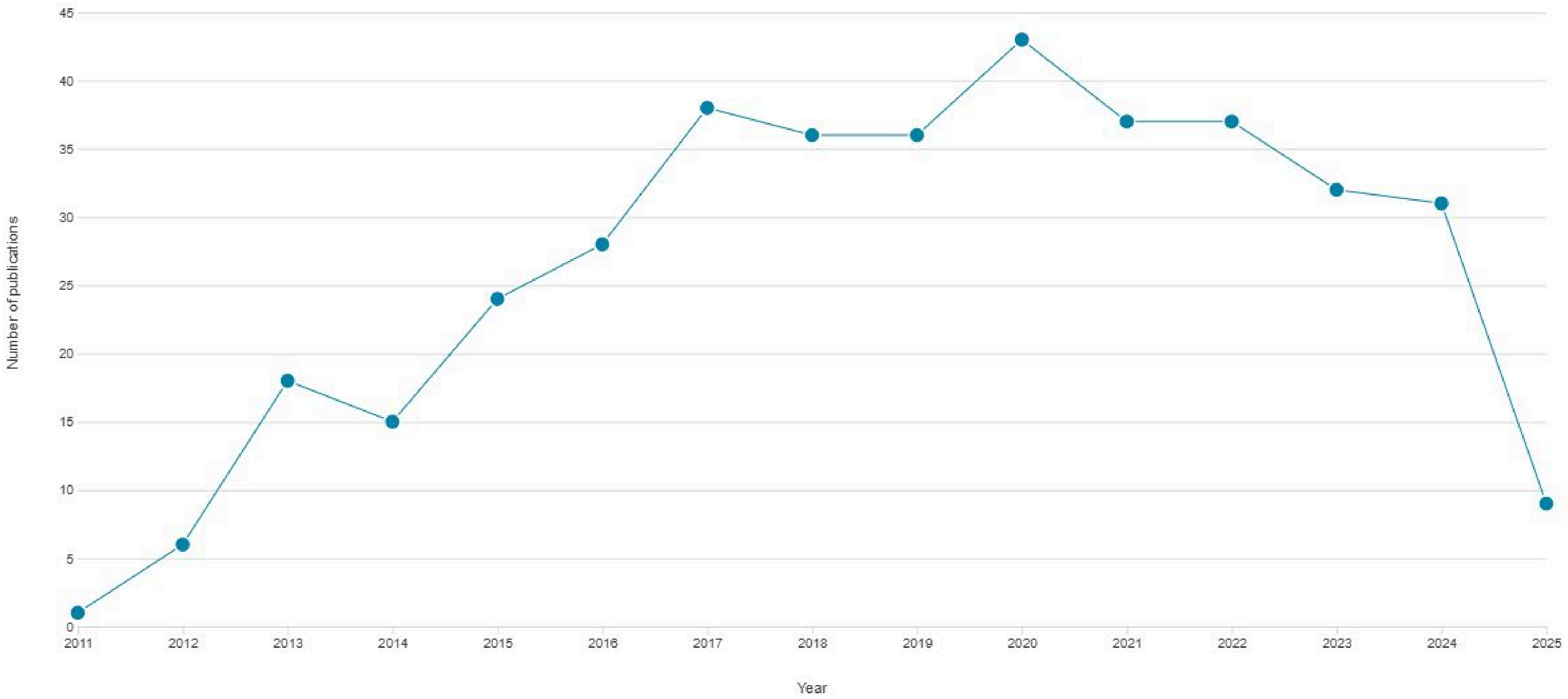


Fraunhofer INT

Emerging moderately promising technology

Airborne wind & kites

Publications



Document Set: Airborne wind & kites
Date: July 18, 2025
Source: KATI developed by Fraunhofer INT

Fraunhofer INT

Emerging moderately promising technology

Solid-state wind energy technologies

Search

Search Query: SPUB=(TAC=("**solid-state wind***" OR "**bladeless wind***" OR "**vortex-induced vibration***" OR "**electrohydrodynamic wind***" OR "**enclosed wind turbine***") AND (TAC=(**turbine*** OR **generator***)

OR IC8=(**F03D9/30** OR **F03D9/11** OR **F03D9/00** OR **F03D9/25** OR **F03D7** OR **F03D5** OR **F03D13/20** OR **F03D13/10** OR **F03D13/25** OR **F03D17**))

AND ALIVE=(YES))

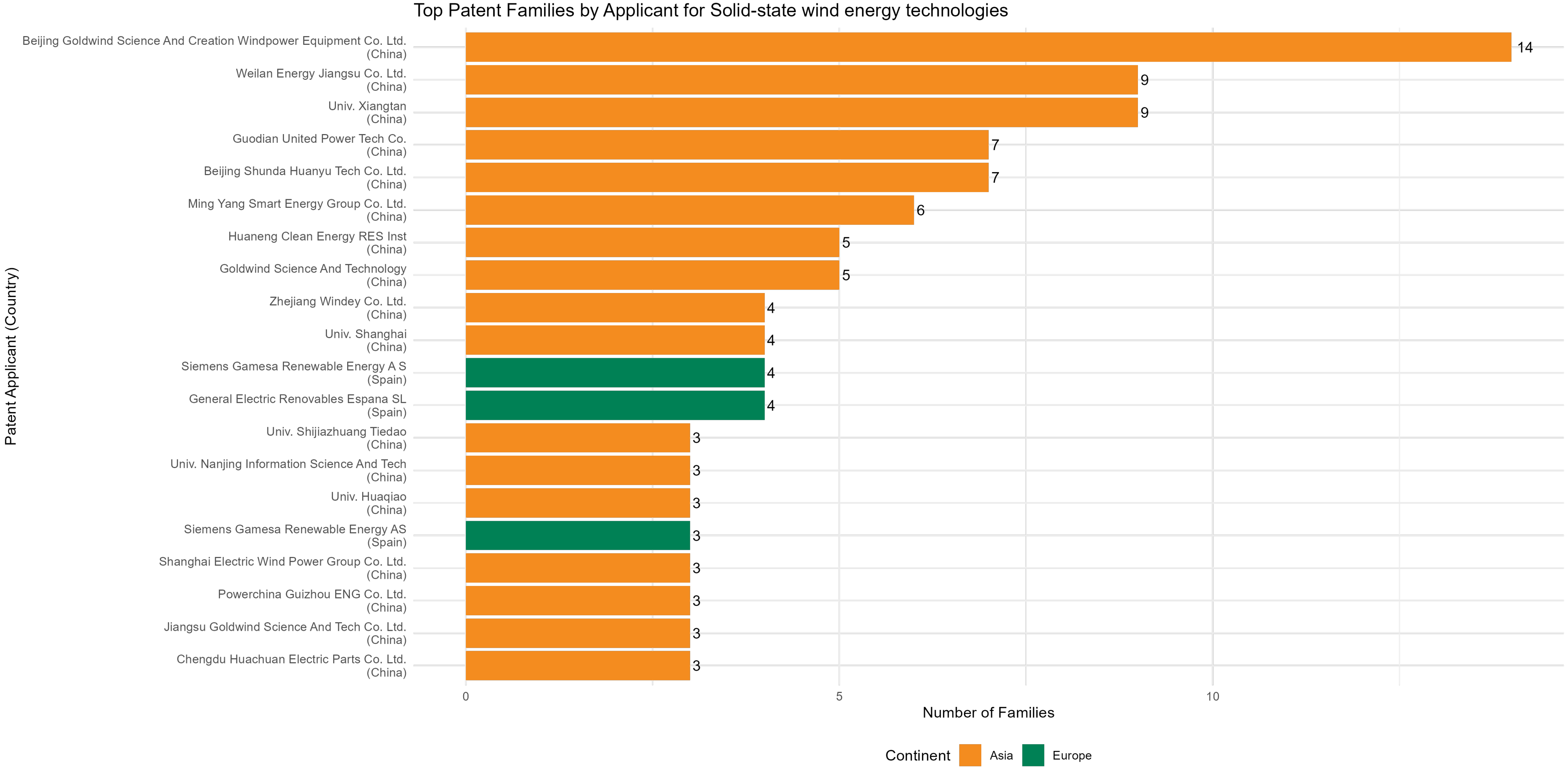
Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 263

Publications: 275

Solid-state wind energy technologies

World actors

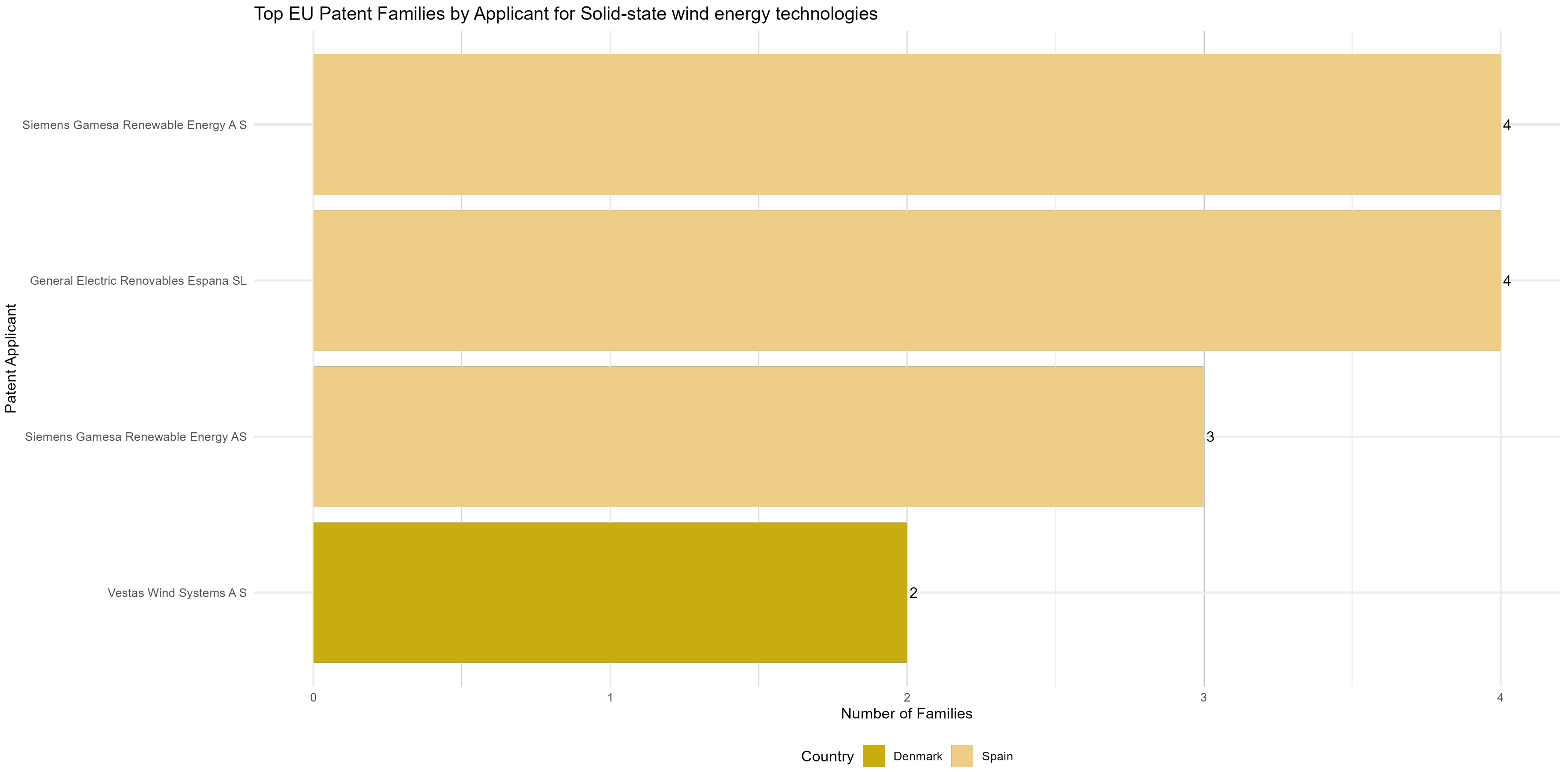


Fraunhofer INT

Emerging moderately promising technology

Solid-state wind energy technologies

Europe actors

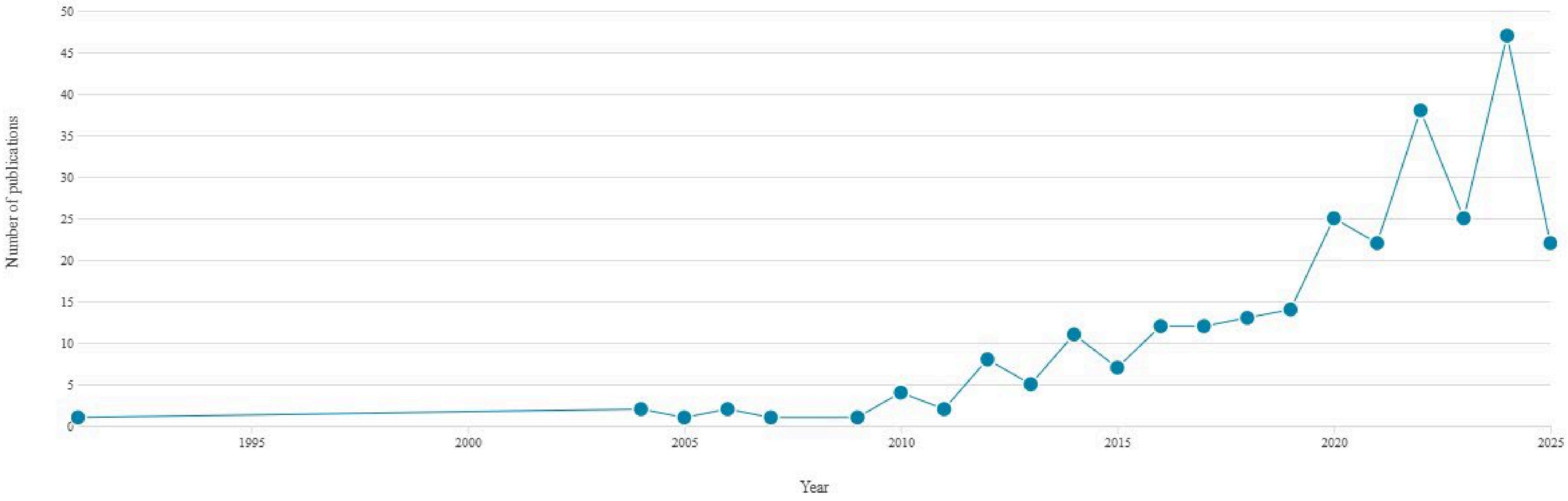


Fraunhofer INT

Emerging moderately promising technology

Solid-state wind energy technologies

Publications



Document Set: Solid-state wind energy technologies
Date: July 31, 2025
Source: KATI developed by Fraunhofer INT

Lithium Sulfur batteries

Search

Search Query: SPUB=(TAC=(("**lithium-sulfur batter***" OR "**Li-S batter***"))

AND CPC=(**Y02E60/10**) AND ALIVE=(YES))

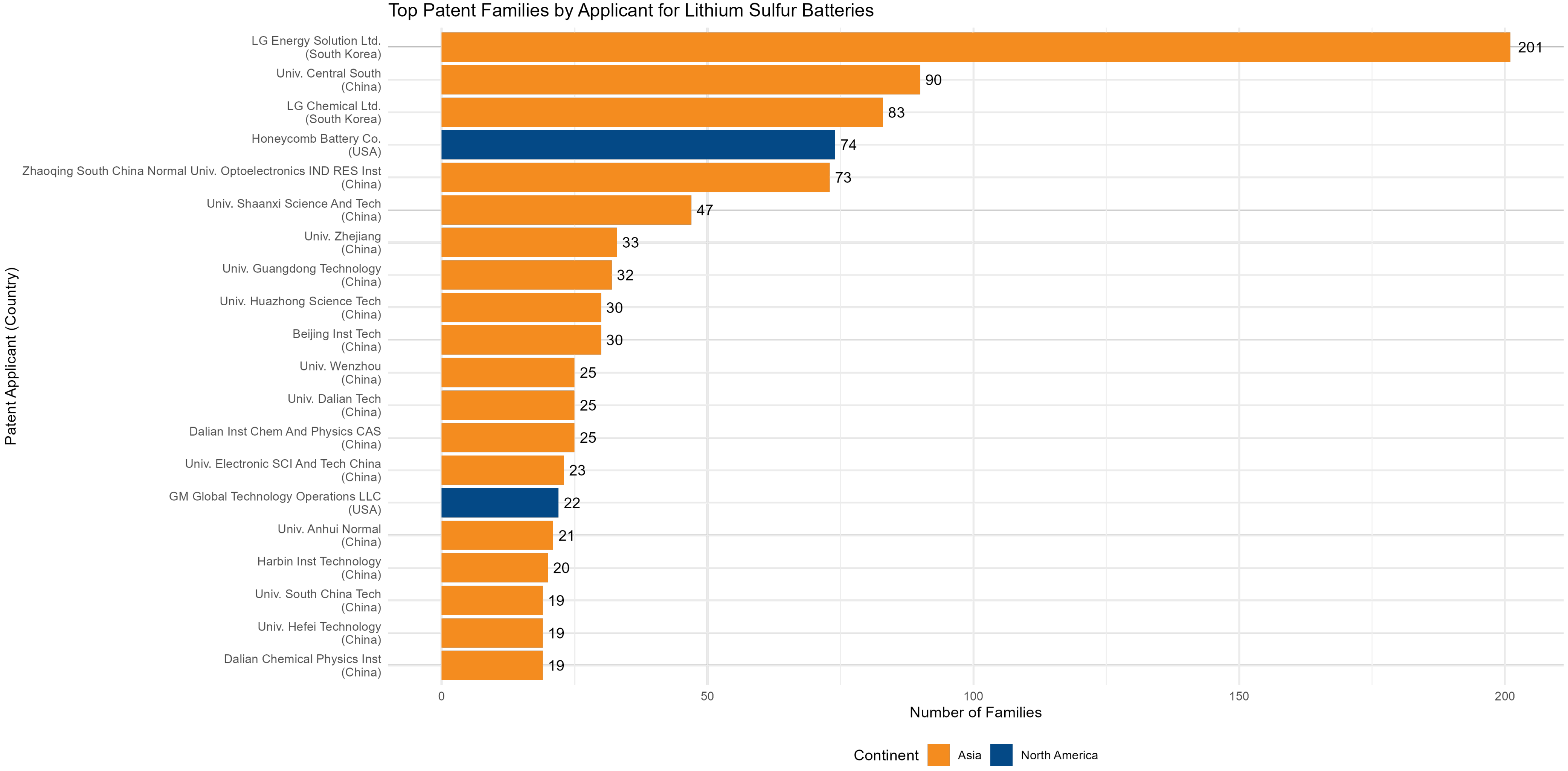
Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 3174

Publications: 14244

Lithium Sulfur batteries

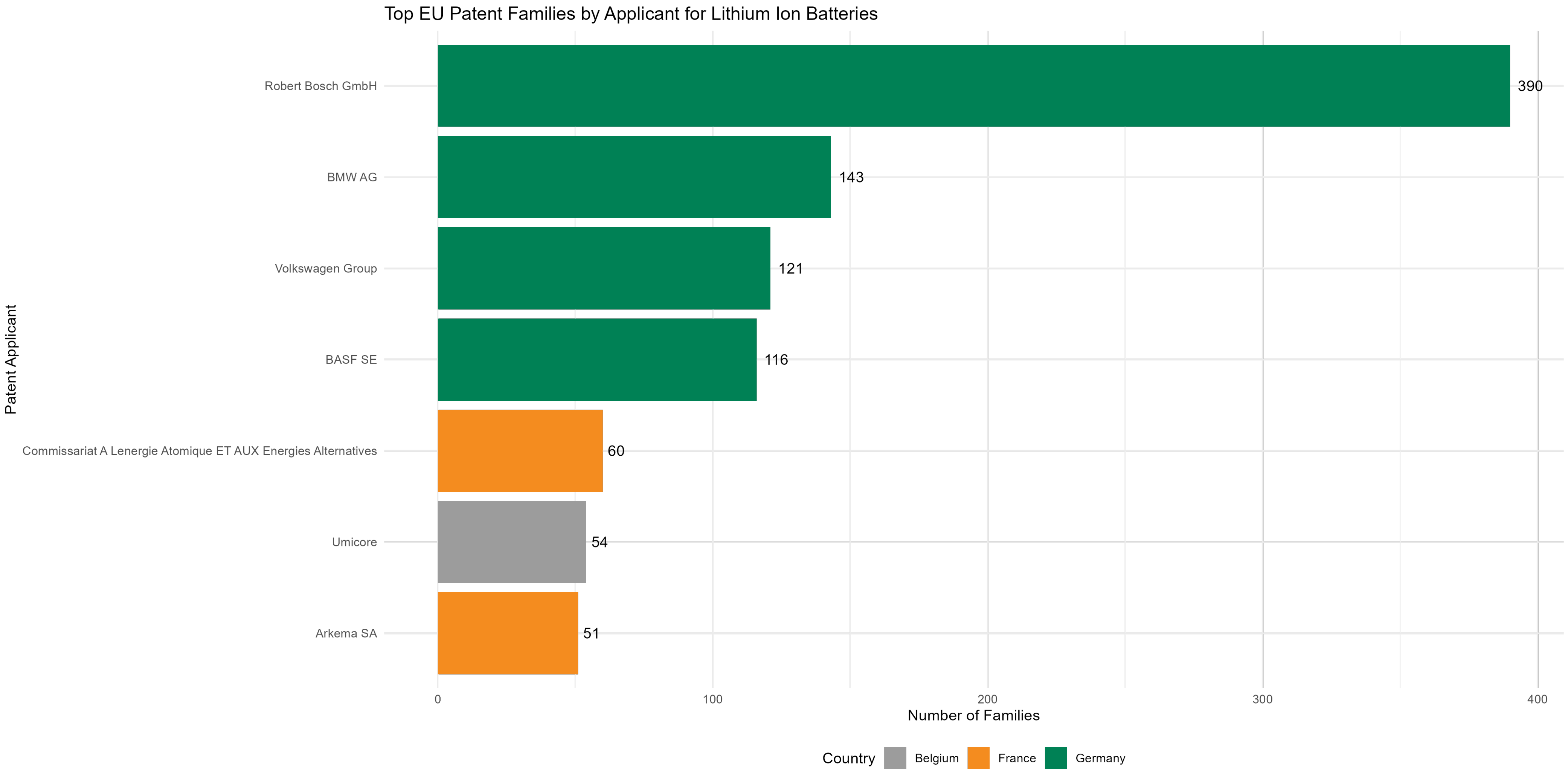
World actors



Lithium Sulfur batteries

Europe actors

Emerging moderately promising technology

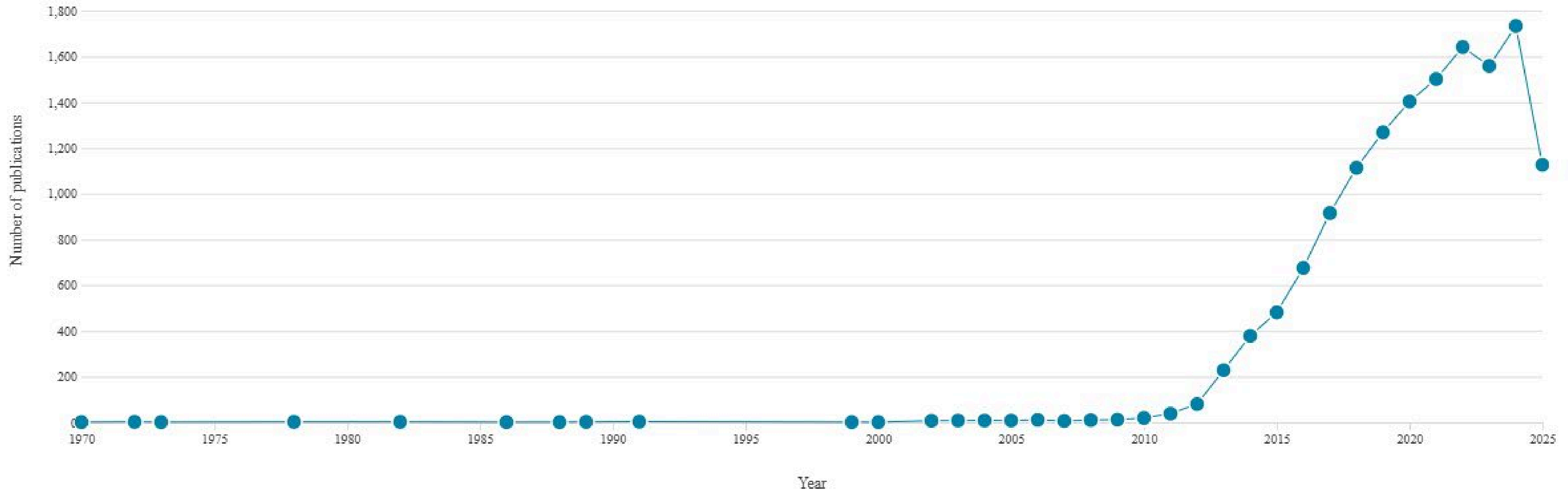


Fraunhofer INT

Emerging moderately promising technology

Lithium Sulfur batteries

Publications



Document Set: Lithium Sulfur batteries
Date: July 31, 2025
Source: KATI developed by Fraunhofer INT

Fraunhofer INT

Emerging moderately promising technology

Metal-Air Batteries

Search

Search Query: SPUB=(TAC=("**metal-air batter***" OR "**zinc-air batter***" OR "**lithium-air batter***" OR "**aluminum-air batter***" OR "**iron-air batter***" OR "**magnesium-air batter***")

AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 3512

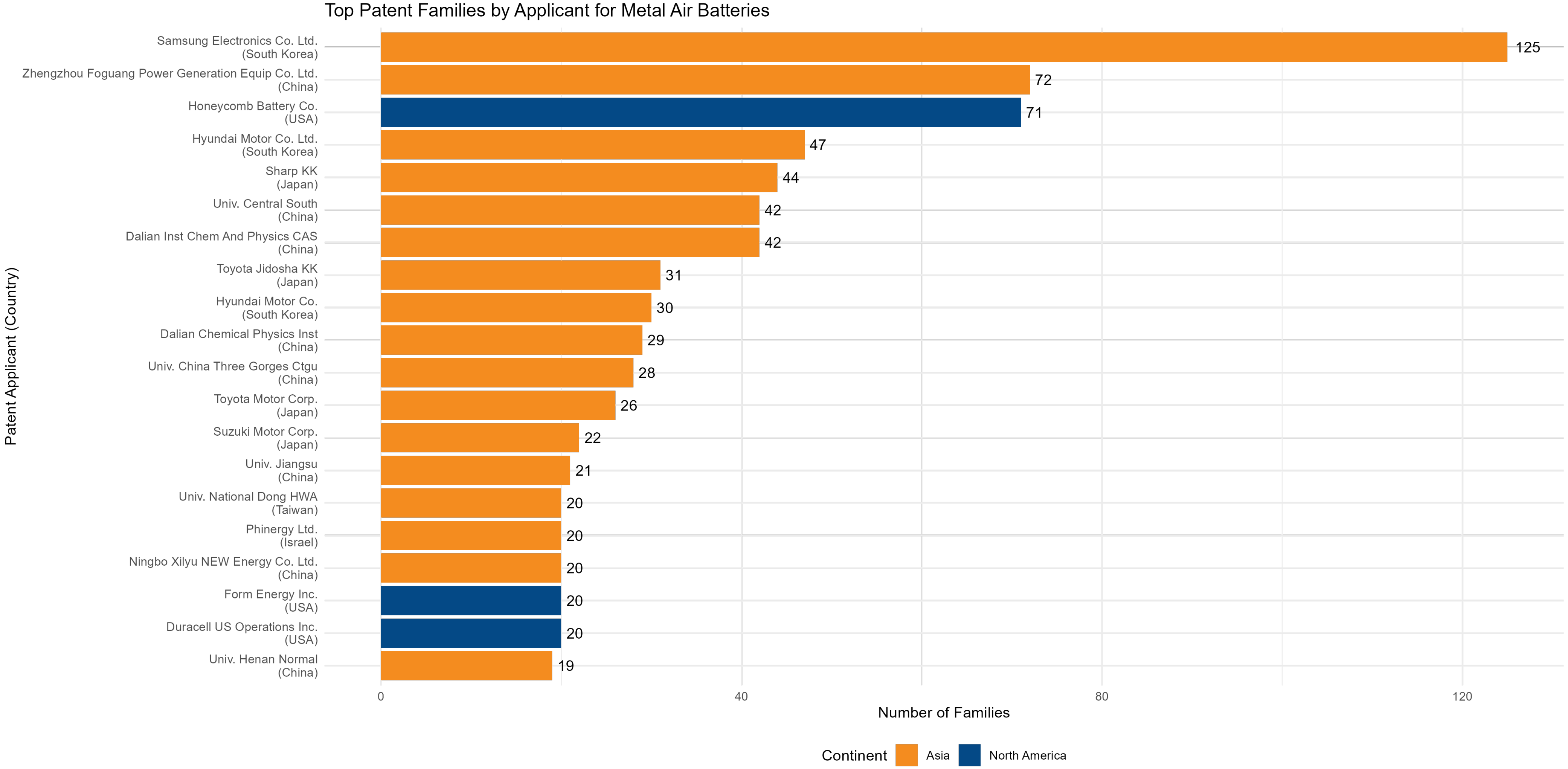
Publications: 9424

Fraunhofer INT

Metal-Air Batteries

World actors

Emerging moderately promising technology



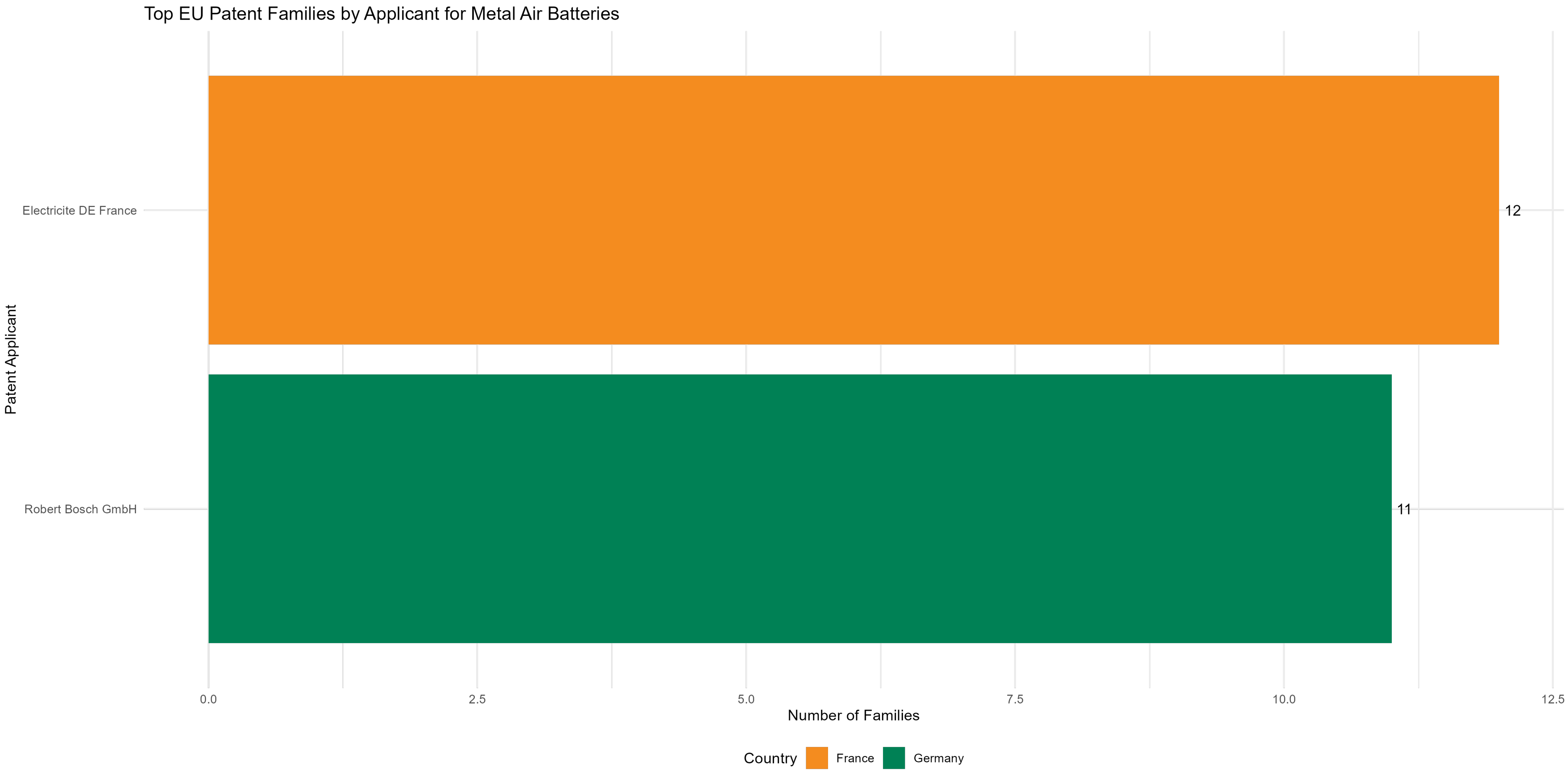
 15.09.2025

Fraunhofer INT

Emerging moderately promising technology

Metal-Air Batteries

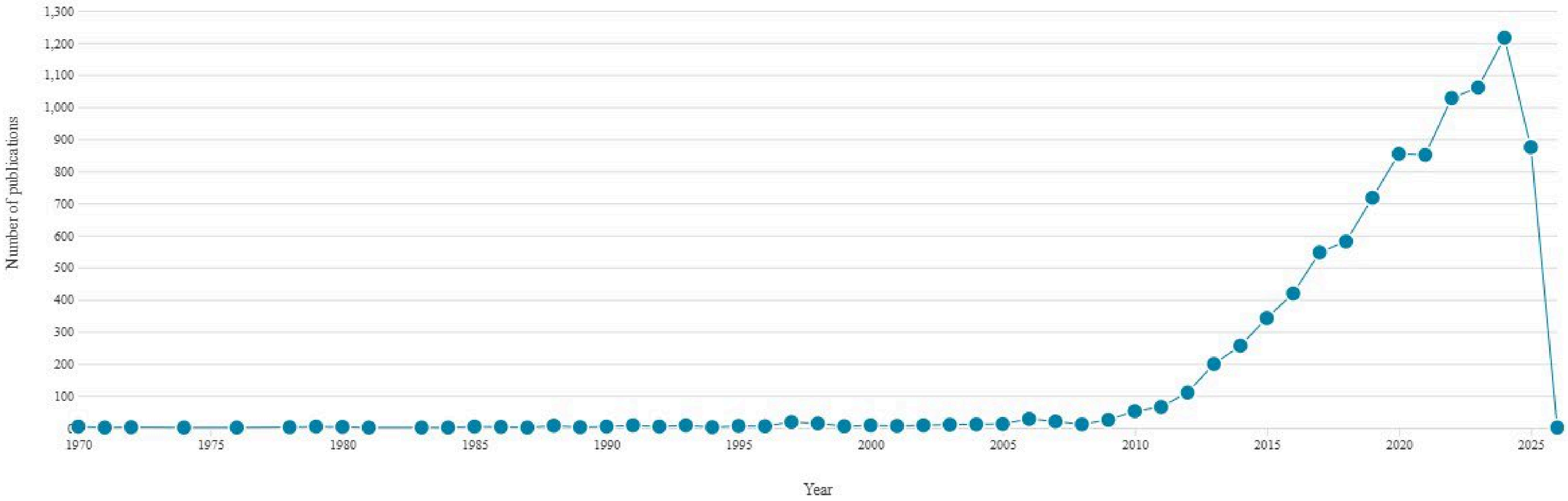
Europe actors



Fraunhofer INT

Metal-Air Batteries

Publications



Document Set: Metal-Air Batteries
Date: July 31, 2025
Source: KATI developed by Fraunhofer INT

Emerging moderately promising technology

Hydrogen-fueled internal combustion engines (H2 ICEs)

Search

Search Query: SPUB=(TAC=("**hydrogen combustion engine***" OR "**H2 ICE**" OR "**hydrogen-fueled engine***" OR "**hydrogen-fueled combustion engine***" OR (("**internal combustion engine***" AND **hydrogen***) AND (**NOx** OR **knocking** OR **backfire**)))

AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 431

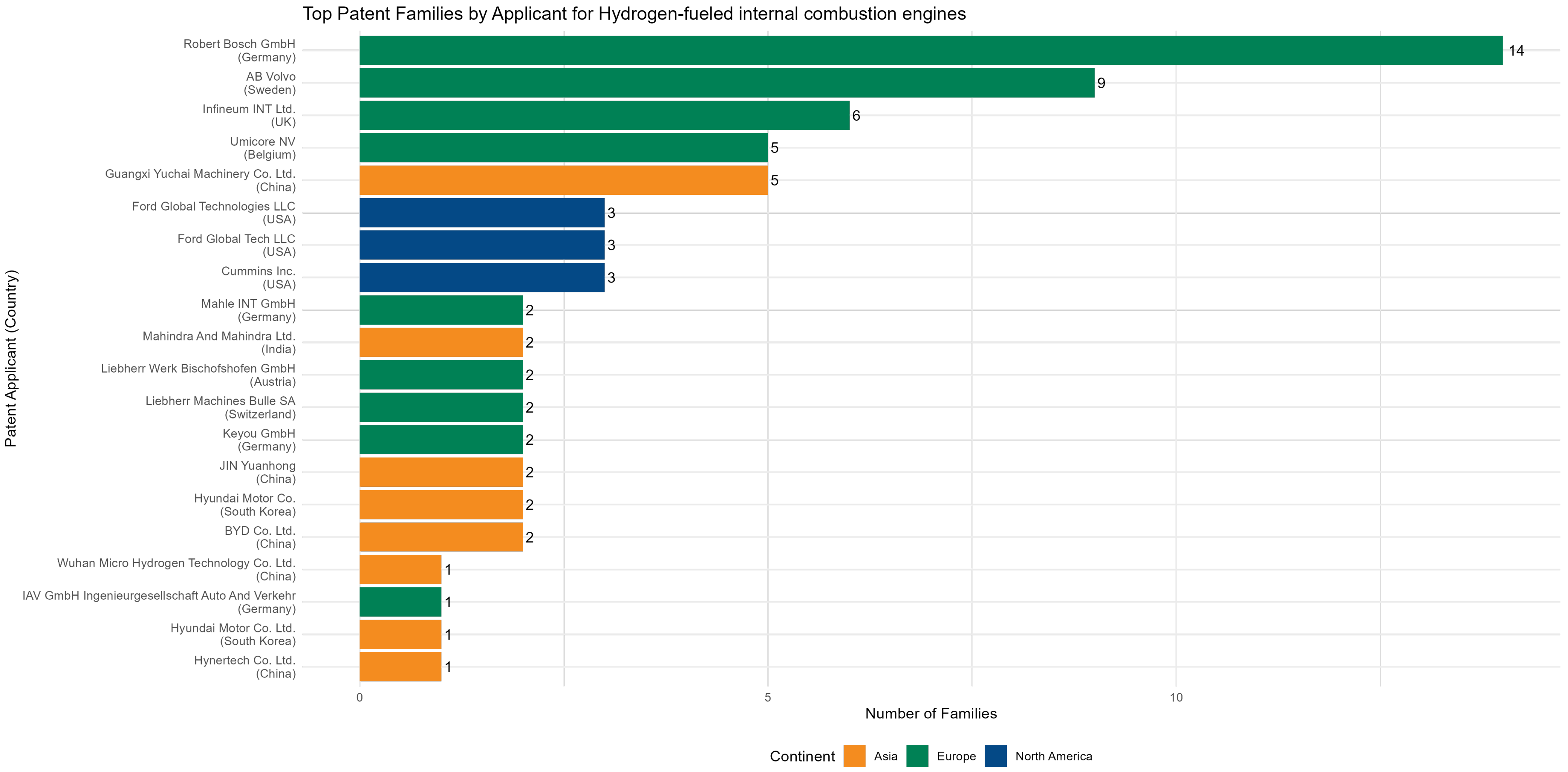
Publications: 891

Fraunhofer INT

Emerging moderately promising technology

Hydrogen-fueled internal combustion engines (H2 ICEs)

World actors



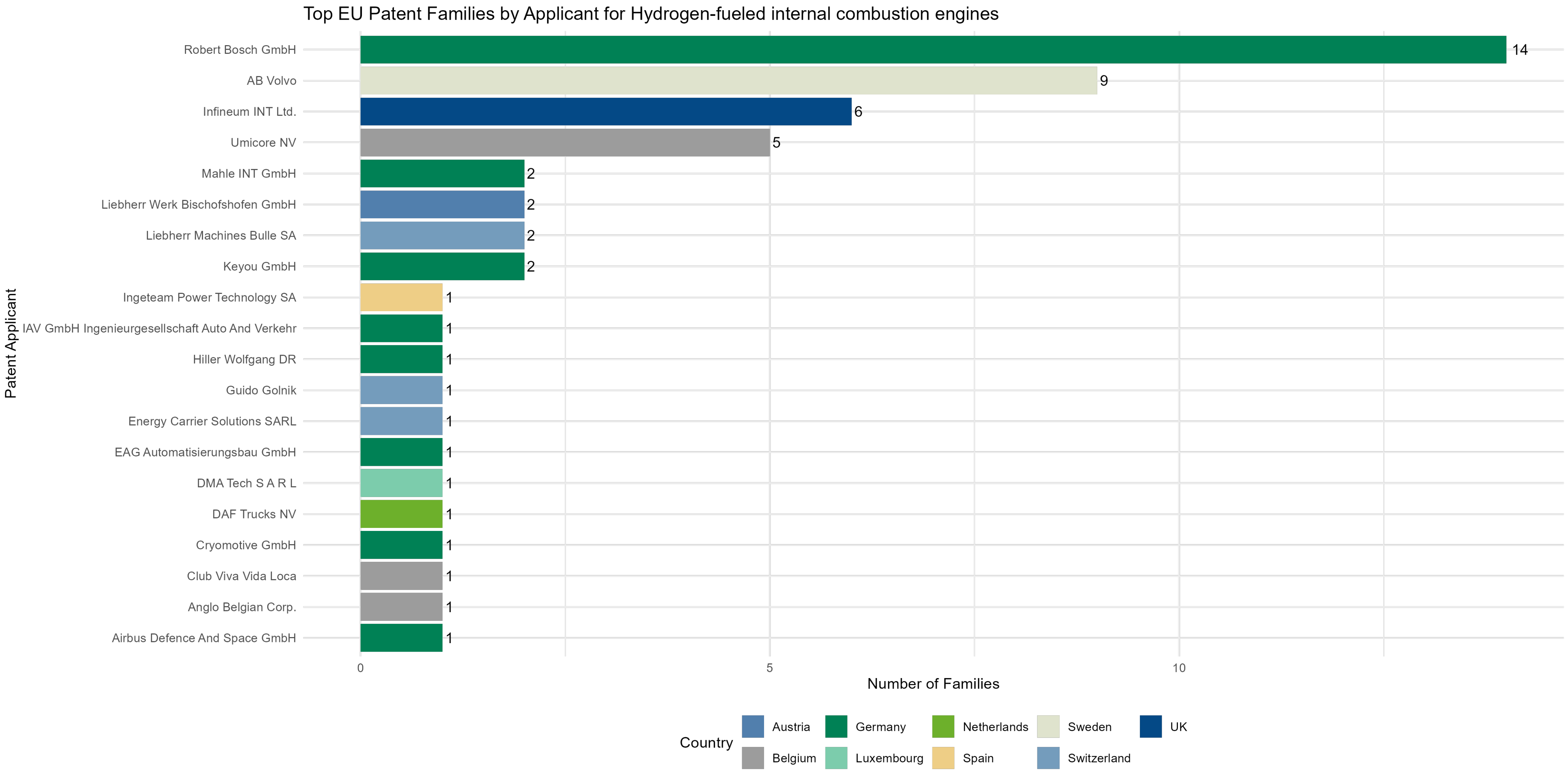
 15.09.2025

Fraunhofer INT

Emerging moderately promising technology

Hydrogen-fueled internal combustion engines (H2 ICEs)

Europe actors

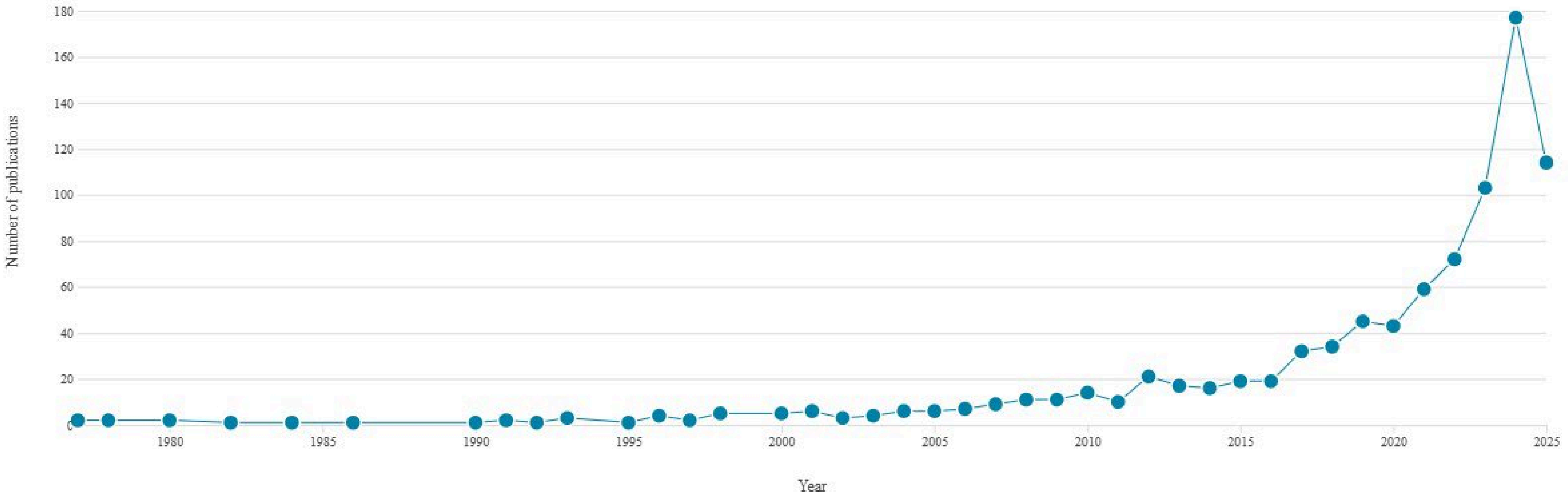


Fraunhofer INT

Hydrogen-fueled internal combustion engines (H2 ICEs)

Publications

Emerging moderately promising technology



Document Set: Hydrogen-fueled internal combustion engines (H2 ICEs)
Date: July 31, 2025
Source: KATI developed by Fraunhofer INT

Emerging moderately promising technology

Methanol

Search

Search Query: SPUB=(TAC=((**methanol*** AND ("**internal combustion engine***" OR "**power-to-liquid***" OR "**ptl**")))

AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

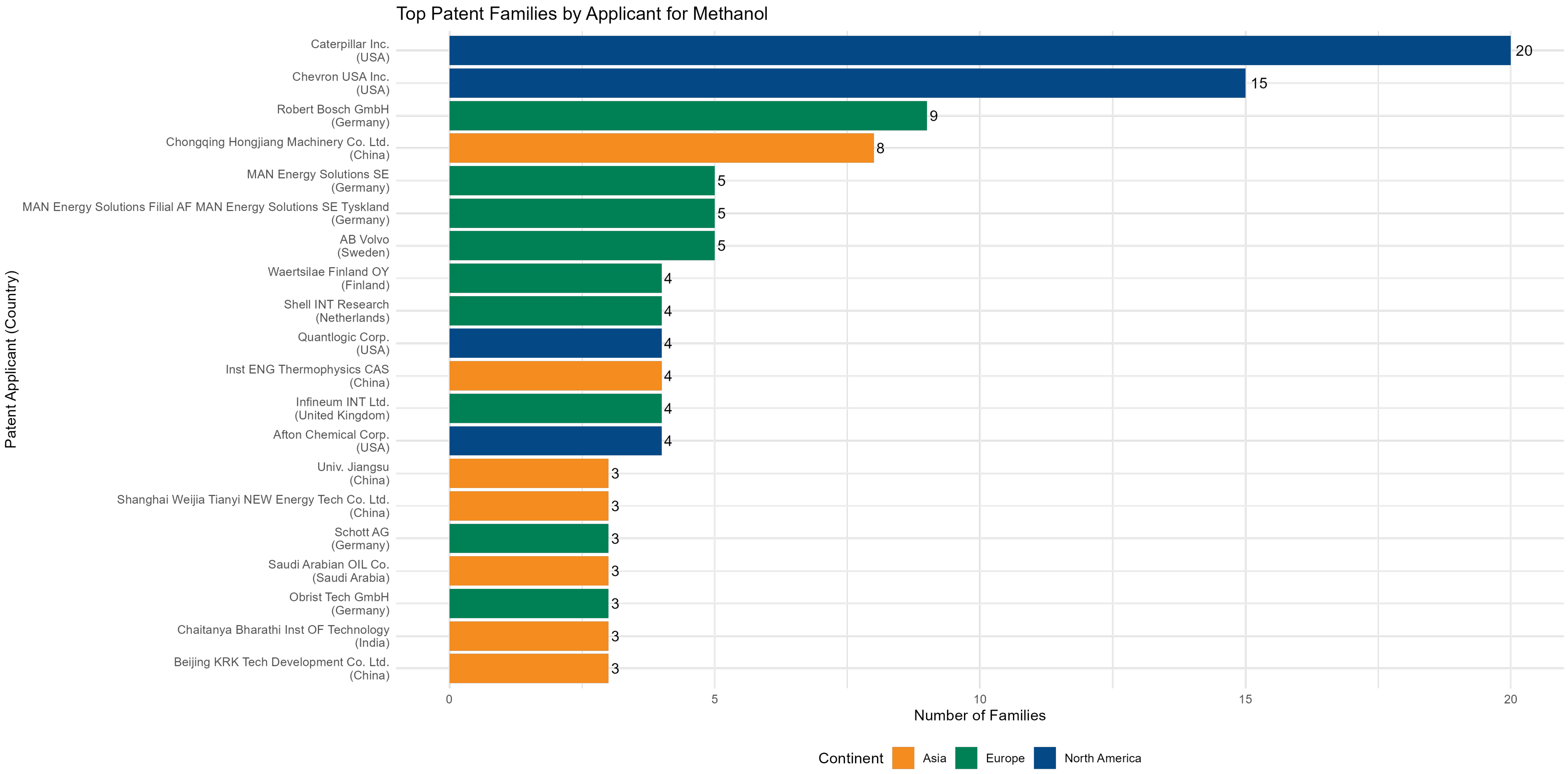
Patentfamilies: 424

Publications: 646

Emerging moderately promising technology

Methanol

World actors

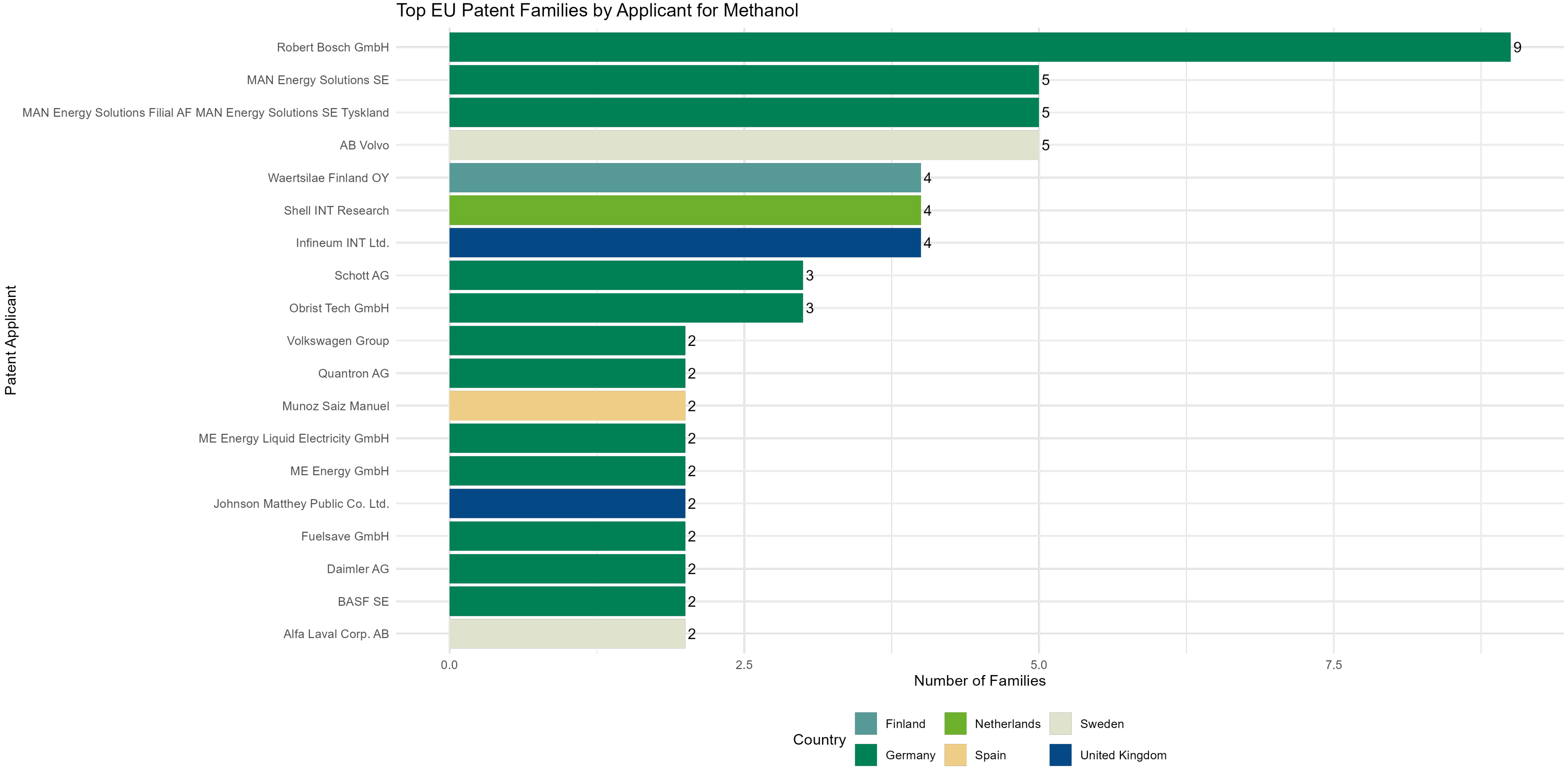


Fraunhofer INT

Emerging moderately promising technology

Methanol

Europe actors



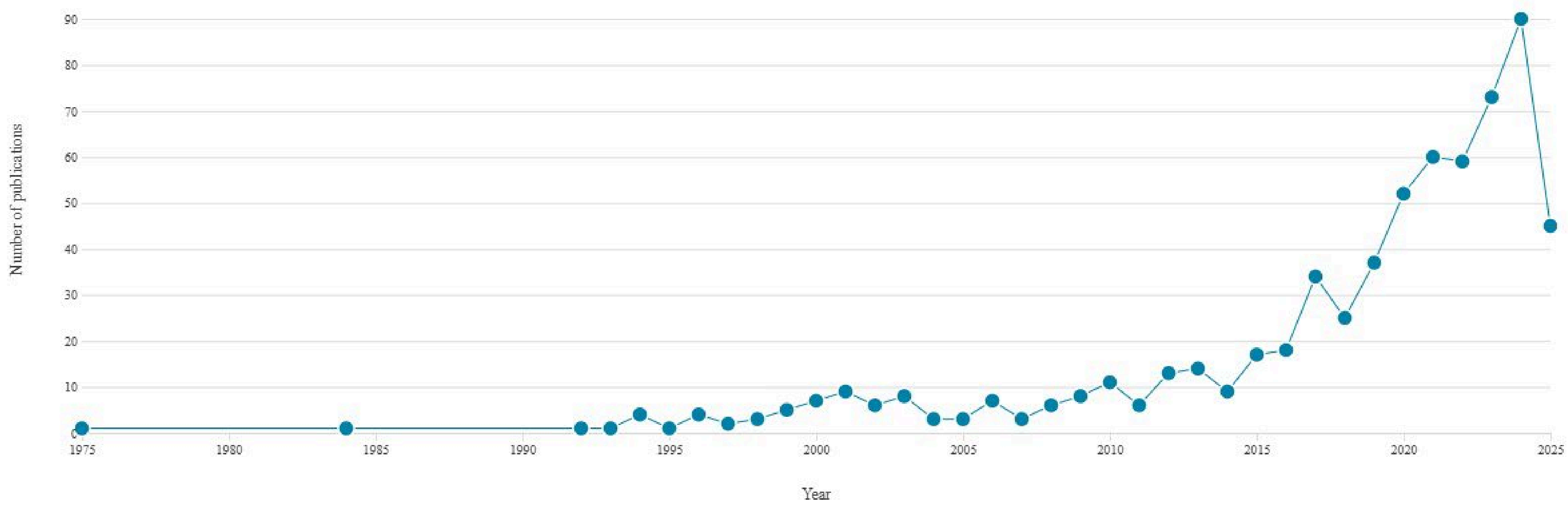
 15.09.2025

Fraunhofer INT

Emerging moderately promising technology

Methanol

Publications



Document Set: Methanol
Date: July 31, 2025
Source: KATI developed by Fraunhofer INT

Small modular (nuclear) reactors

Search

Search Query: SPUB=(TAC=("**small modular nuclear reactor***" OR "**mobile nuclear power plant***" OR (("**Small Modular Reactor***" OR "**microreactor***") AND "**nuclear***"))

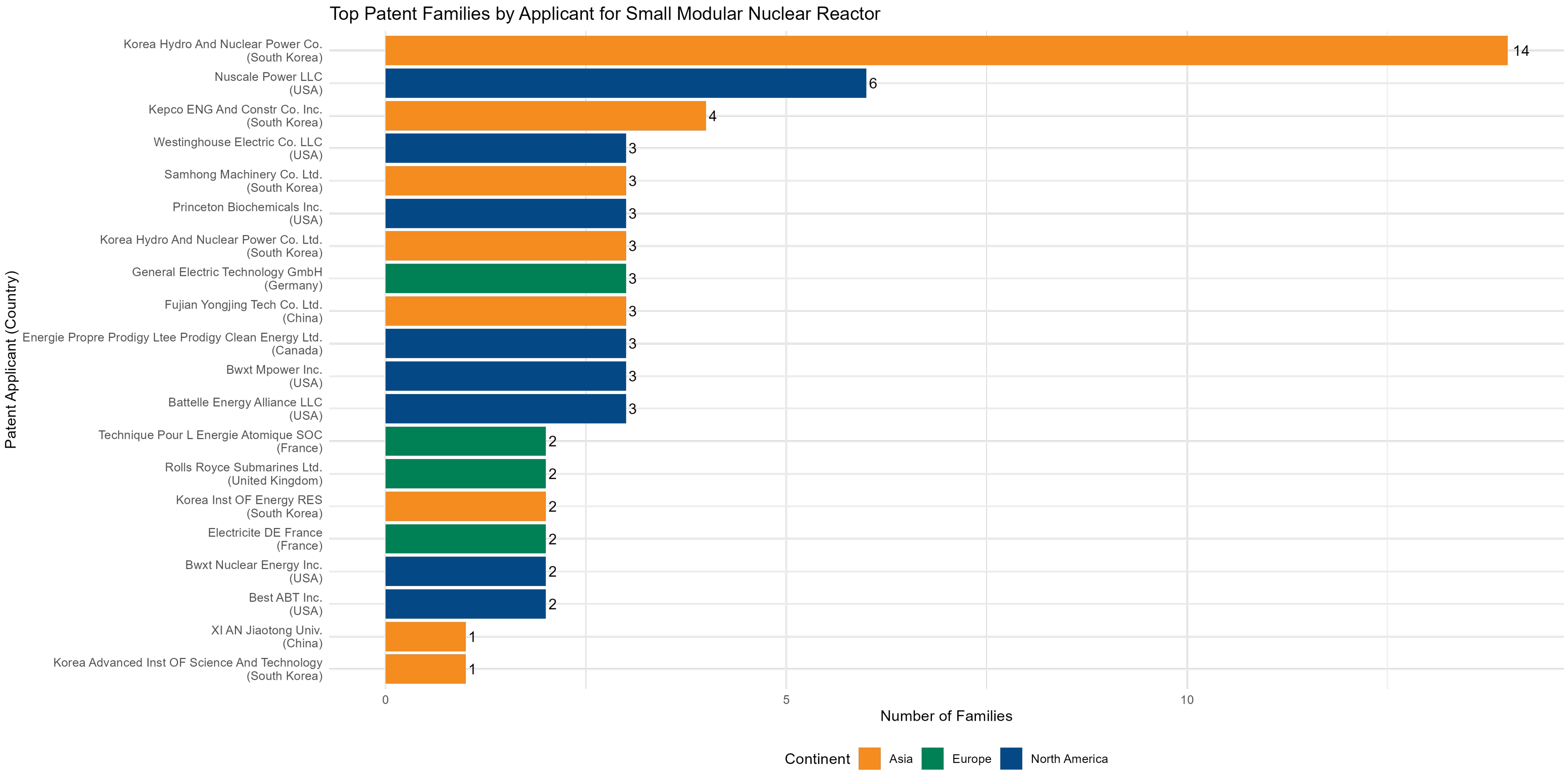
AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 111

Small modular (nuclear) reactors

World actors

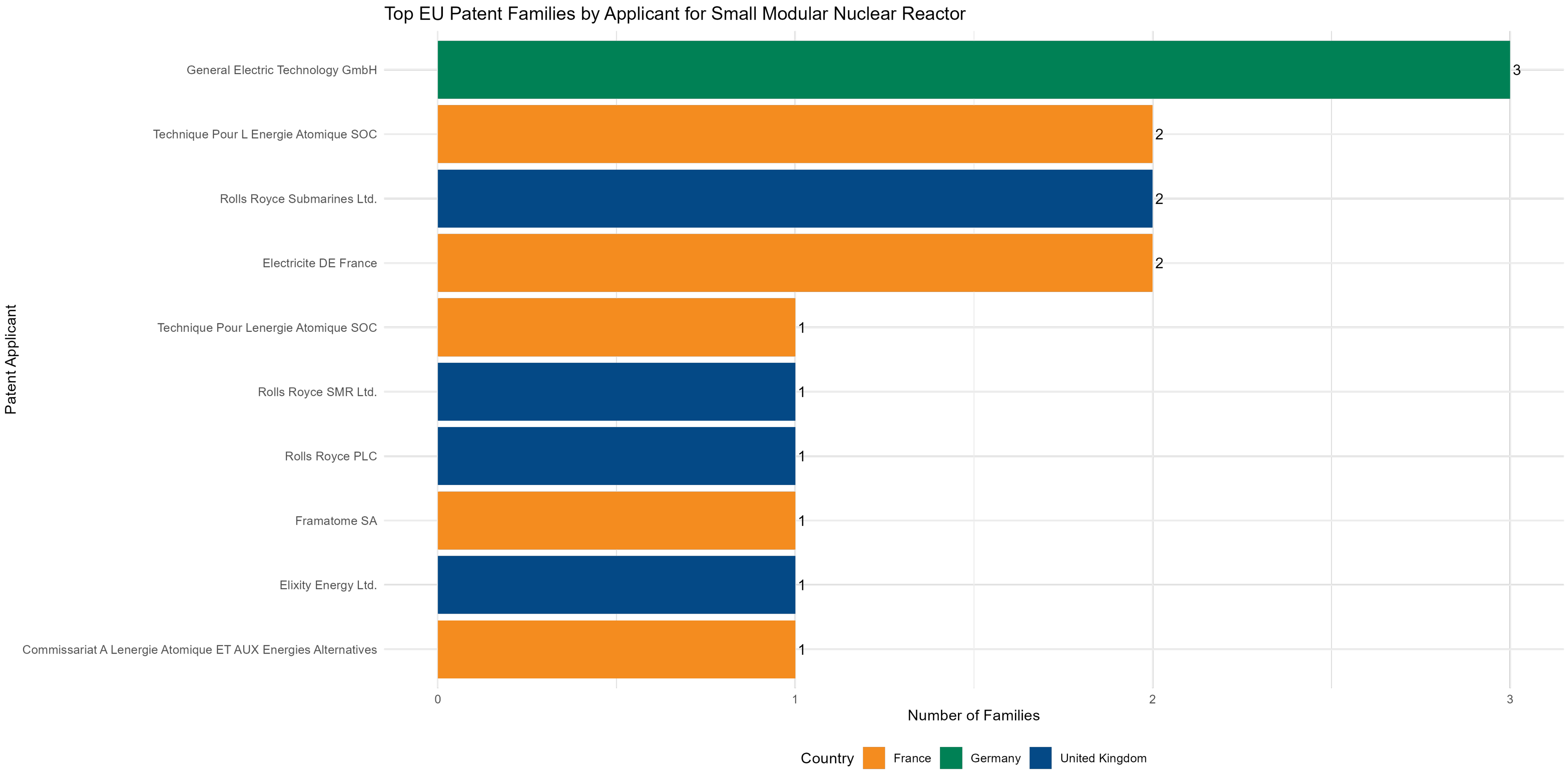


Fraunhofer INT

Emerging lowly promising technology

Small modular (nuclear) reactors

Europe actors



Fraunhofer INT

Emerging lowly promising technology

Tidal Energy Generators

Search

Search Query: SPUB=(TAC=("**Tid* energ* converter***")

OR (IC8=(**F03B13/26**)

AND TAC=("**tidal**" AND "**energ***" AND "**convert***"))

AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

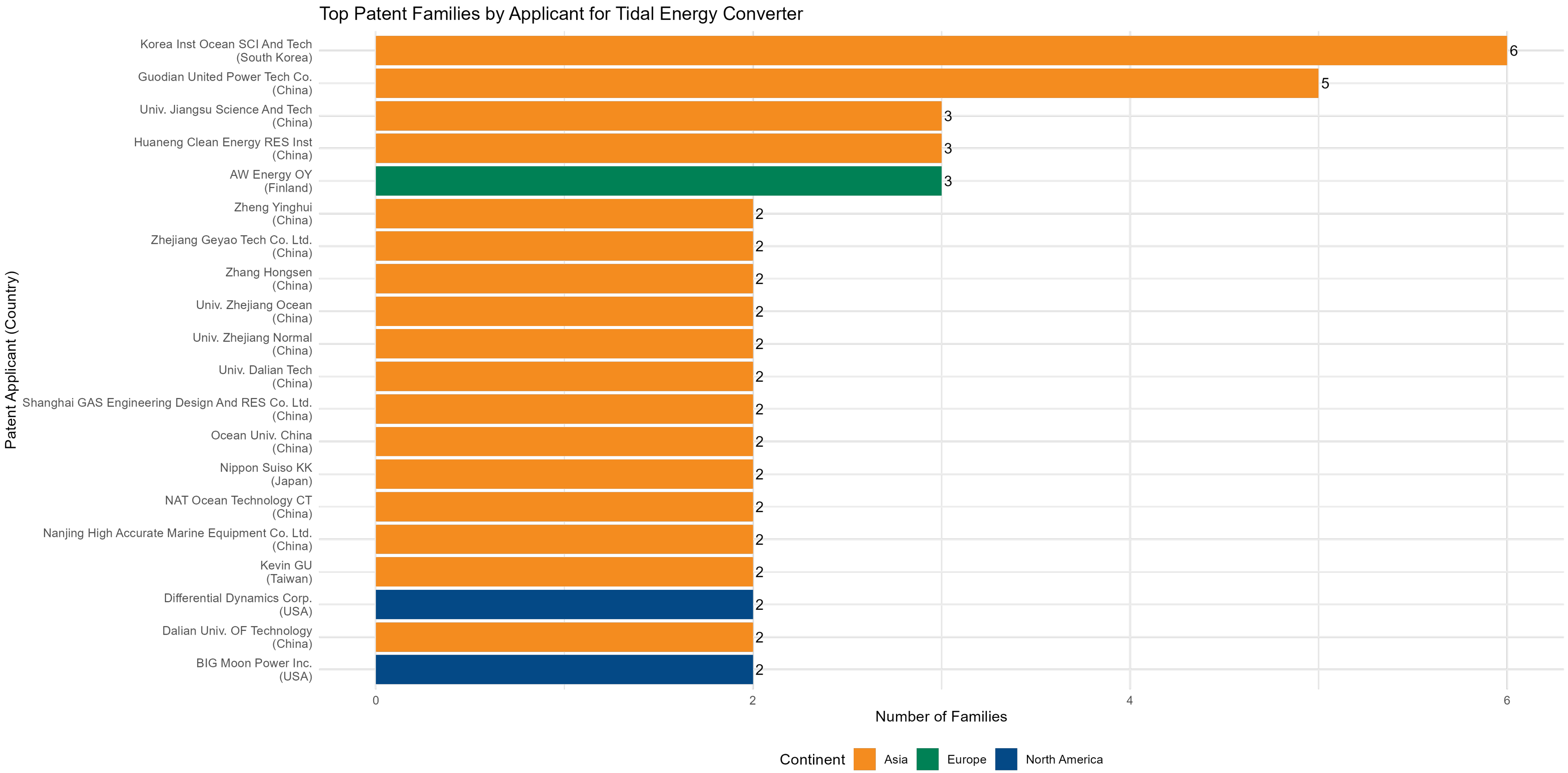
Patentfamilies: 223

Fraunhofer INT

Emerging lowly promising technology

Tidal Energy Generators

World actors

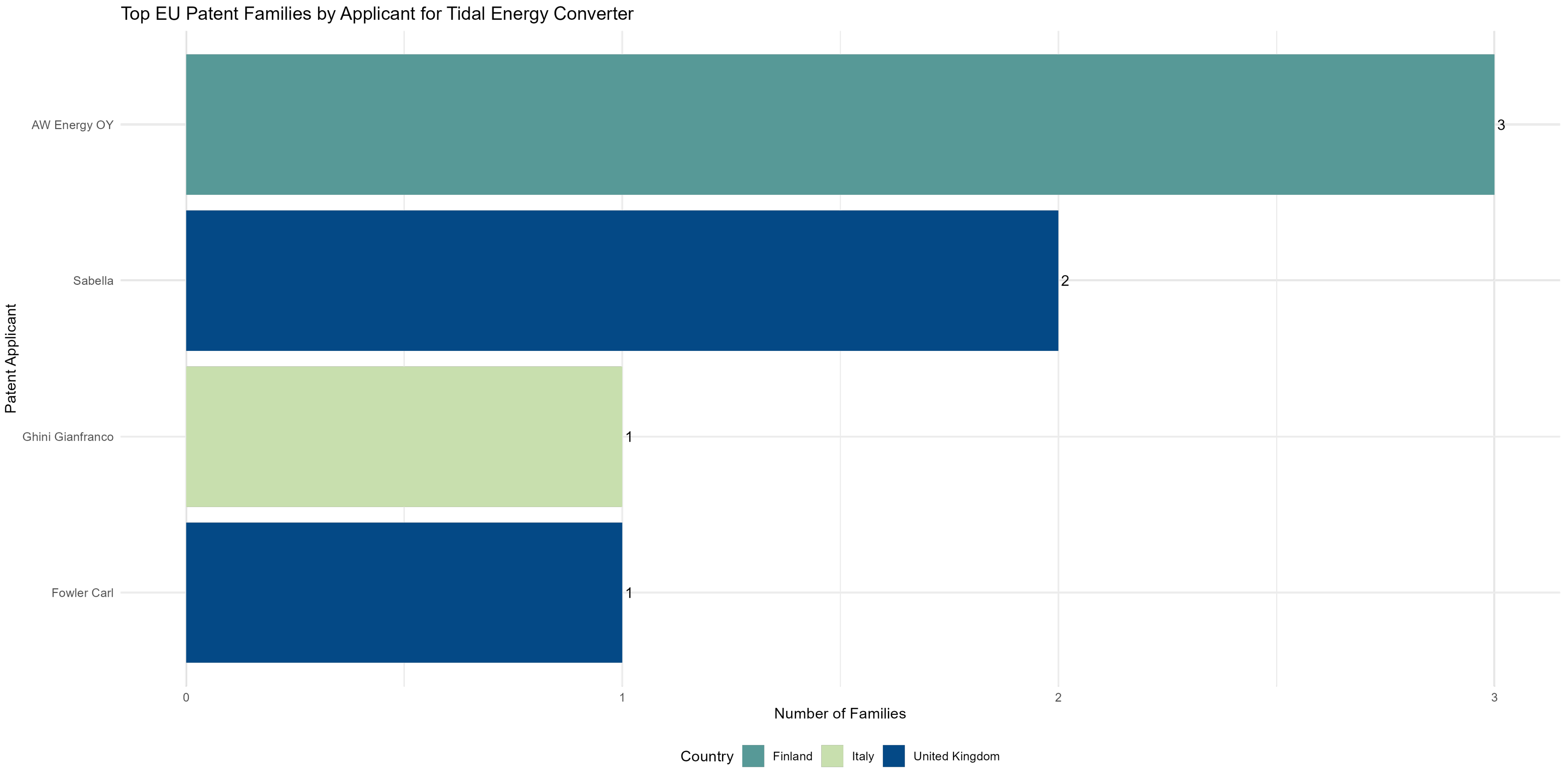


Fraunhofer INT

Tidal Energy Generators

Europe actors

Emerging lowly promising technology



Pedal-powered Generators

Search

Search Query: SPUB=(TAC=(("**pedal-powered generator***" OR "**pedal generator**" OR "**bicycle generator***" OR "**bike-power* electricity**" OR "**human-power* generator***" OR ("**pedal power***" AND "**system**")) NOT "**electric bicycle**")

AND IC8=(H02) AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

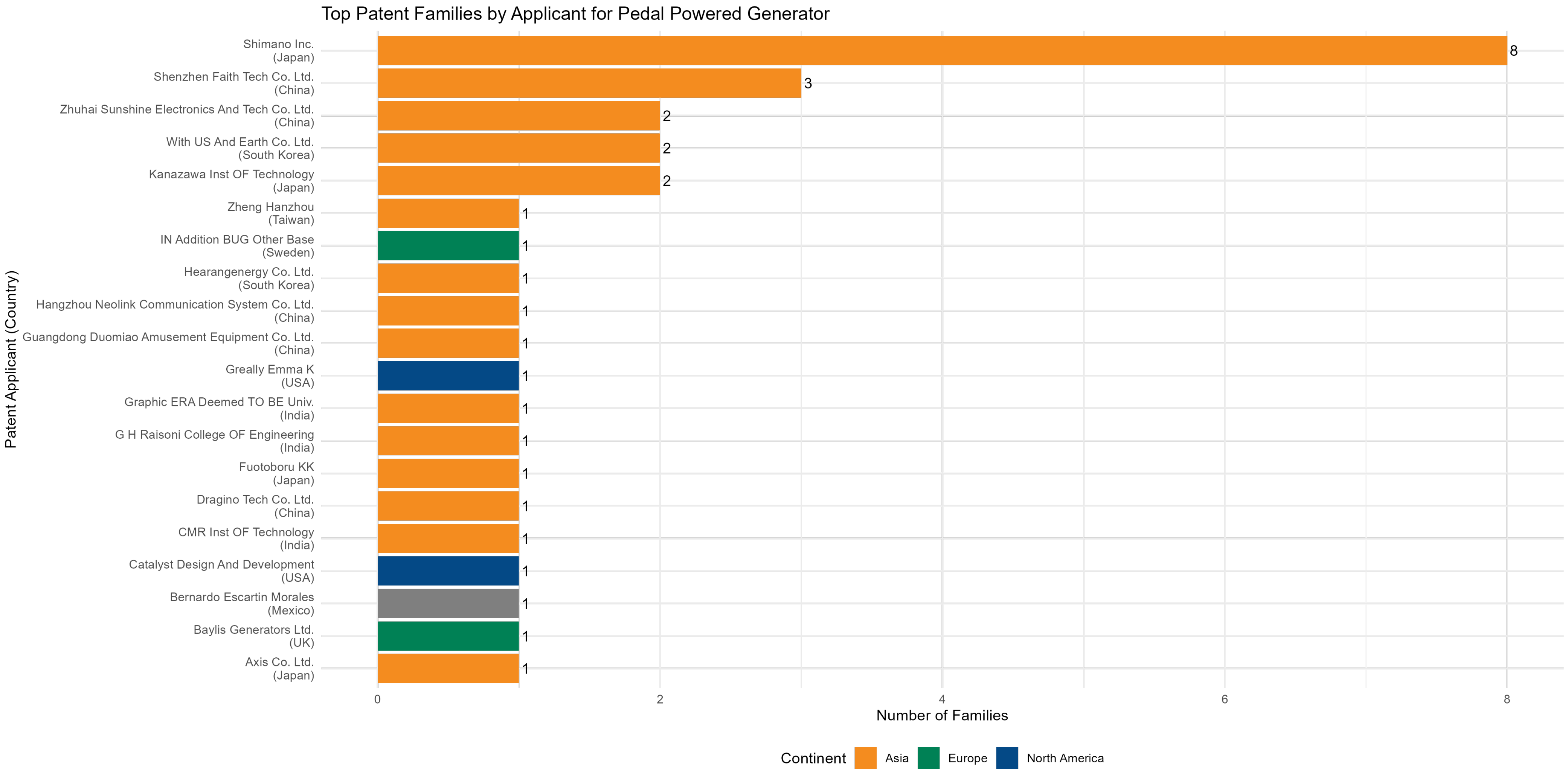
Patentfamilies: 50

Fraunhofer INT

Emerging lowly promising technology

Pedal-powered Generators

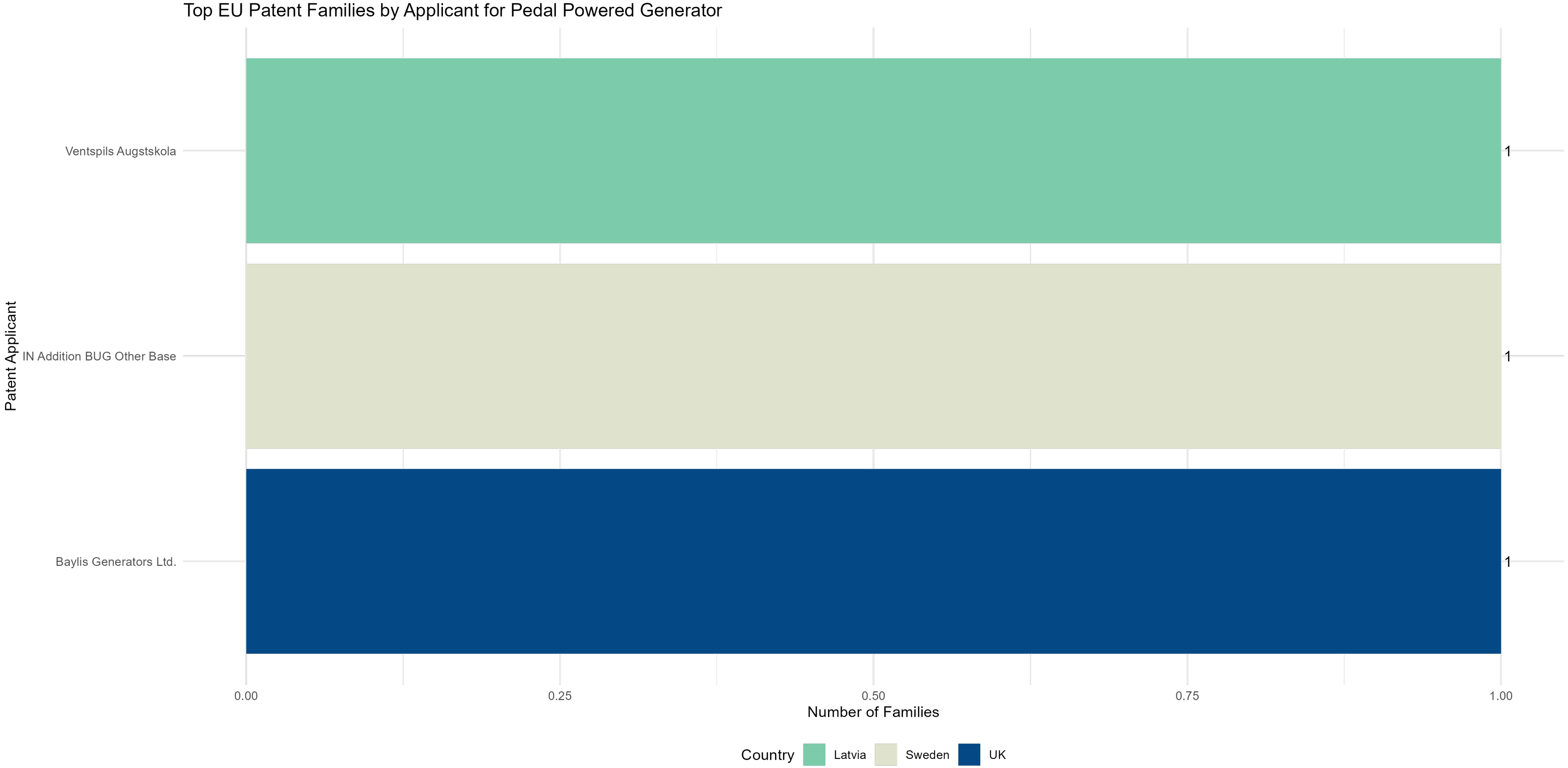
World actors



Fraunhofer INT

Pedal-powered Generators

Europe actors



Fraunhofer INT

Emerging lowly promising technology

Liquid organic hydrogen carriers

Search

Search Query: SPUB=(TAC=(("**liquid organic hydrogen carr***") OR (("**methylcyclohexane**" OR "**toluene**" OR "**dibenzyltoluene**" OR "**perhydro-dibenzyltoluene**" OR "**H18-DBT**") AND ("**hydrogen carr***" OR "**hydrogen stor***" OR "**hydrogen transp***" OR "**reversible hydrogenation***"))) AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

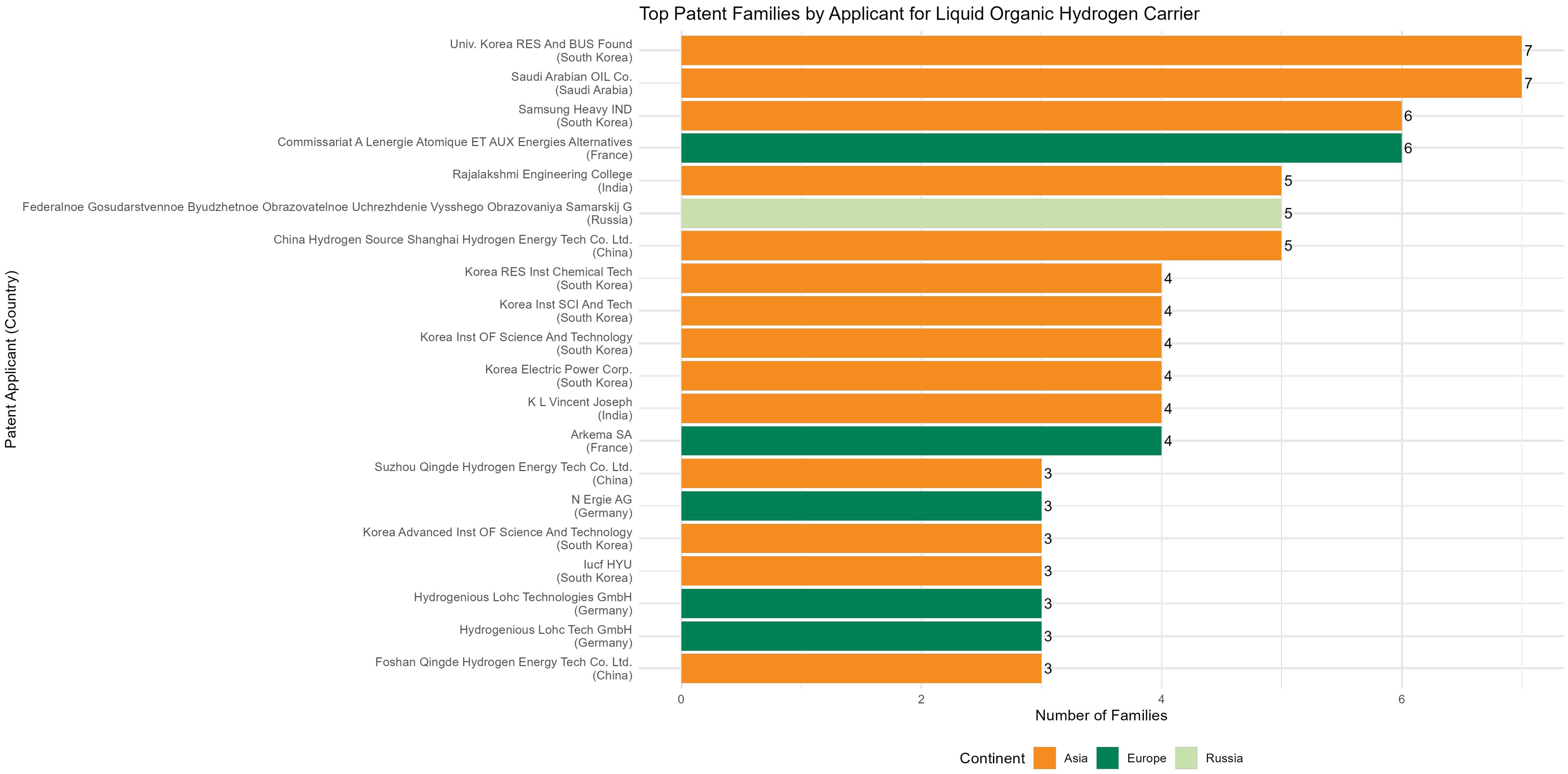
Patentfamilies: 239

Fraunhofer INT

Liquid organic hydrogen carriers

World actors

Emerging lowly promising technology

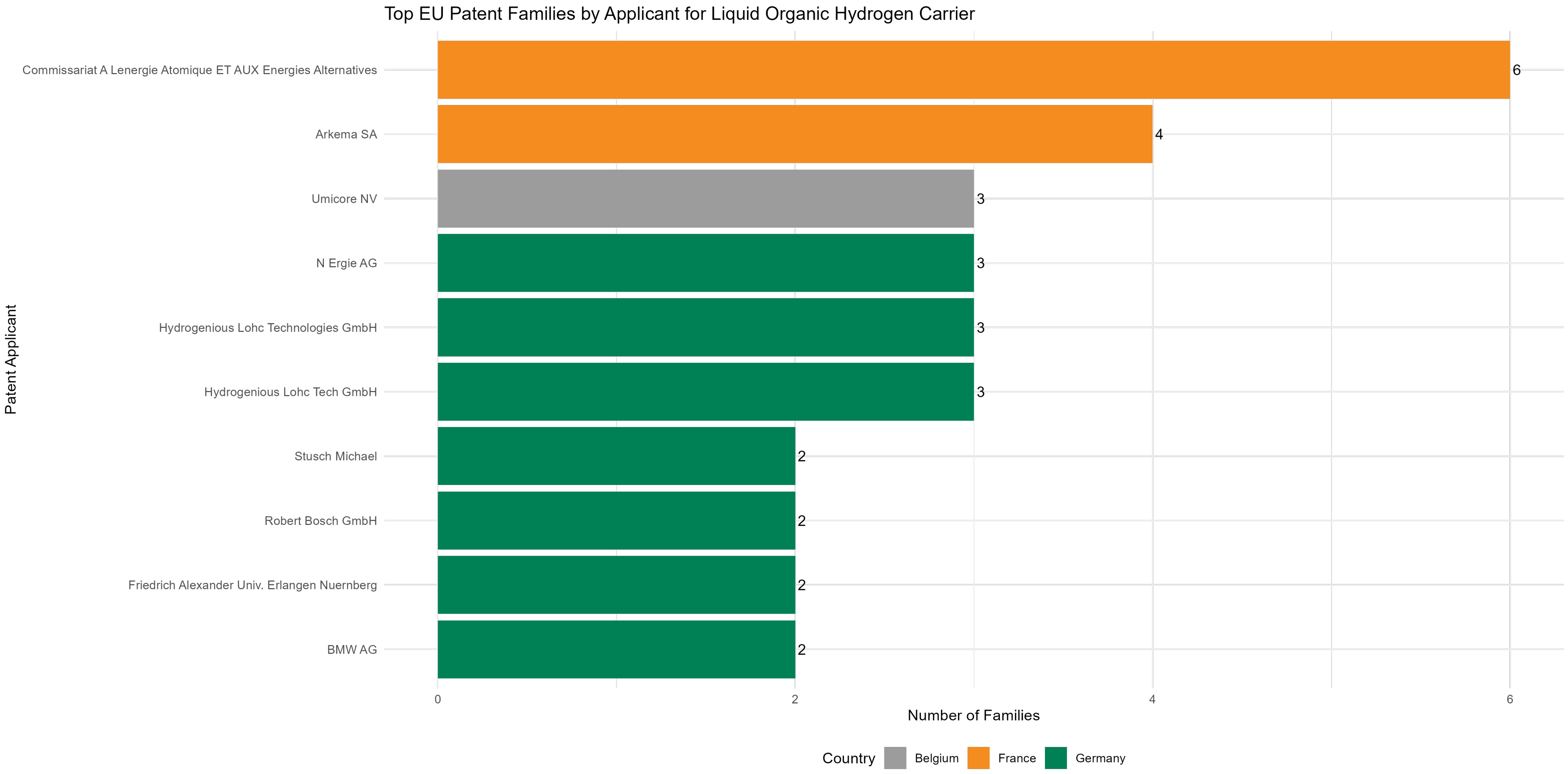


Fraunhofer INT

Emerging lowly promising technology

Liquid organic hydrogen carriers

Europe actors



Fraunhofer INT

Emerging lowly promising technology

E-Fuels

Search

Search Query: SPUB=(TAC=("**electrofuel***" OR ("**synthetic fuel**" AND "**renewable energ***") OR "**power-to-liquid**" OR "**power-to-gas**" OR "**carbon-neutral fuel***") OR (TAC=("**e-fuel**" OR "**e-methane**" OR "**e-methanol**" OR "**e-diesel**")

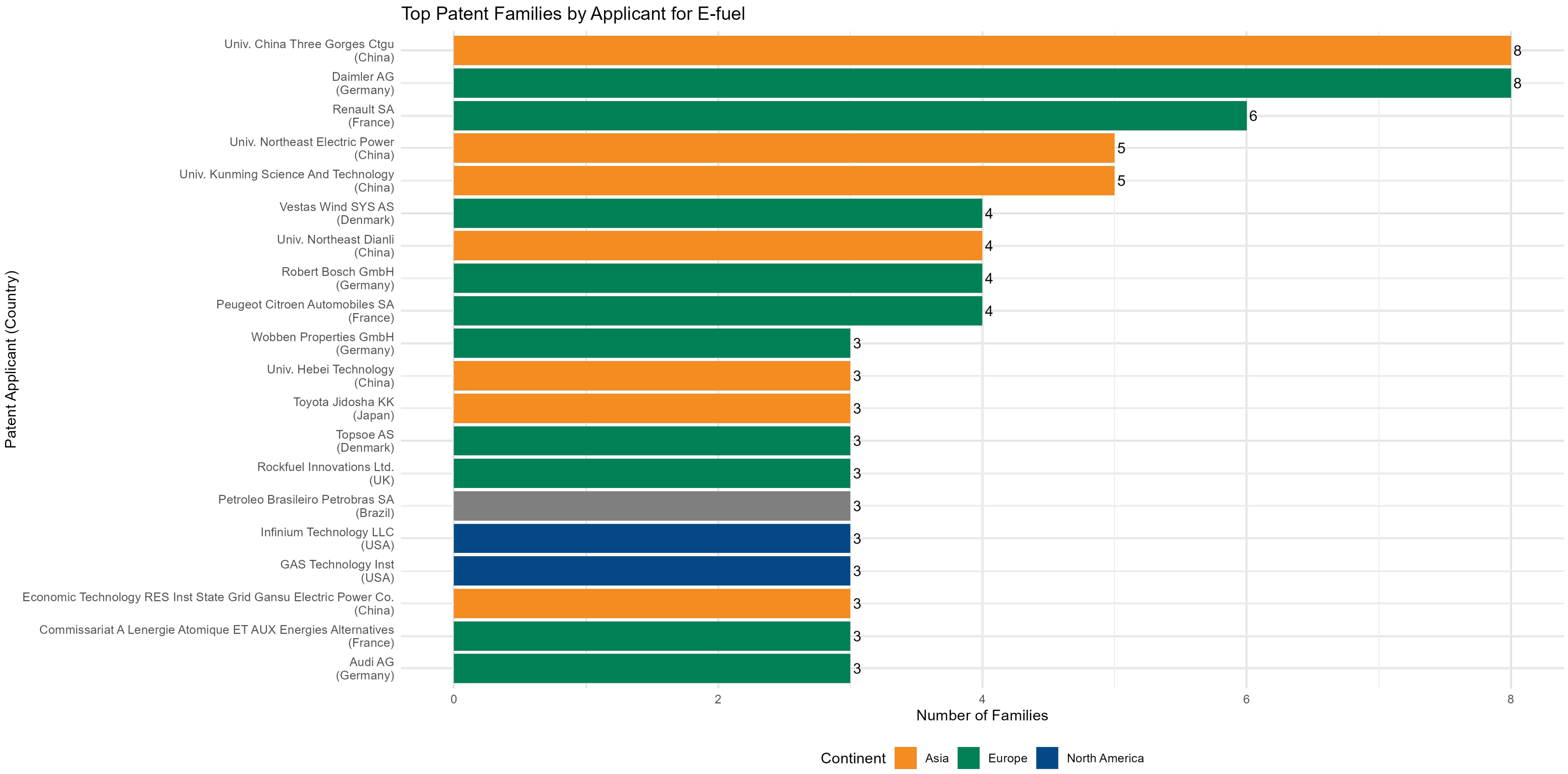
AND CPC=(**Y02**)) AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

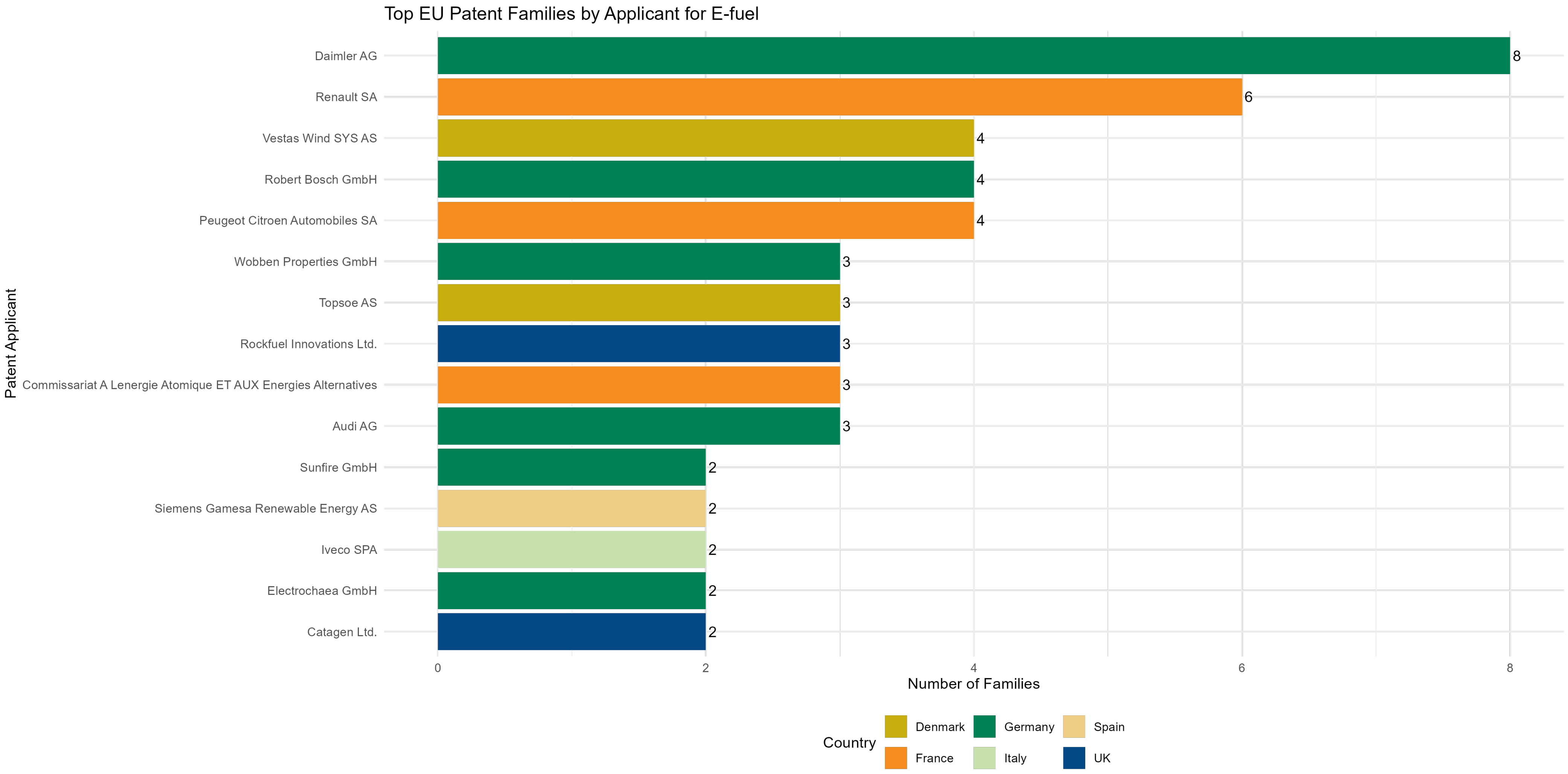
Patentfamilies: 355

Fraunhofer INT

E-Fuels
World actors



E-Fuels
Europe actors



Fraunhofer INT

Emerging lowly promising technology

E-Ammonia

Search

Search Query: SPUB=((TAC=(("**green ammonia**" OR "**electro-ammonia**" OR "**synthetic ammonia**"))

OR CPC=(**C01C1/04**) OR IC8=(**C01C1/04**)) AND ALIVE=(YES))

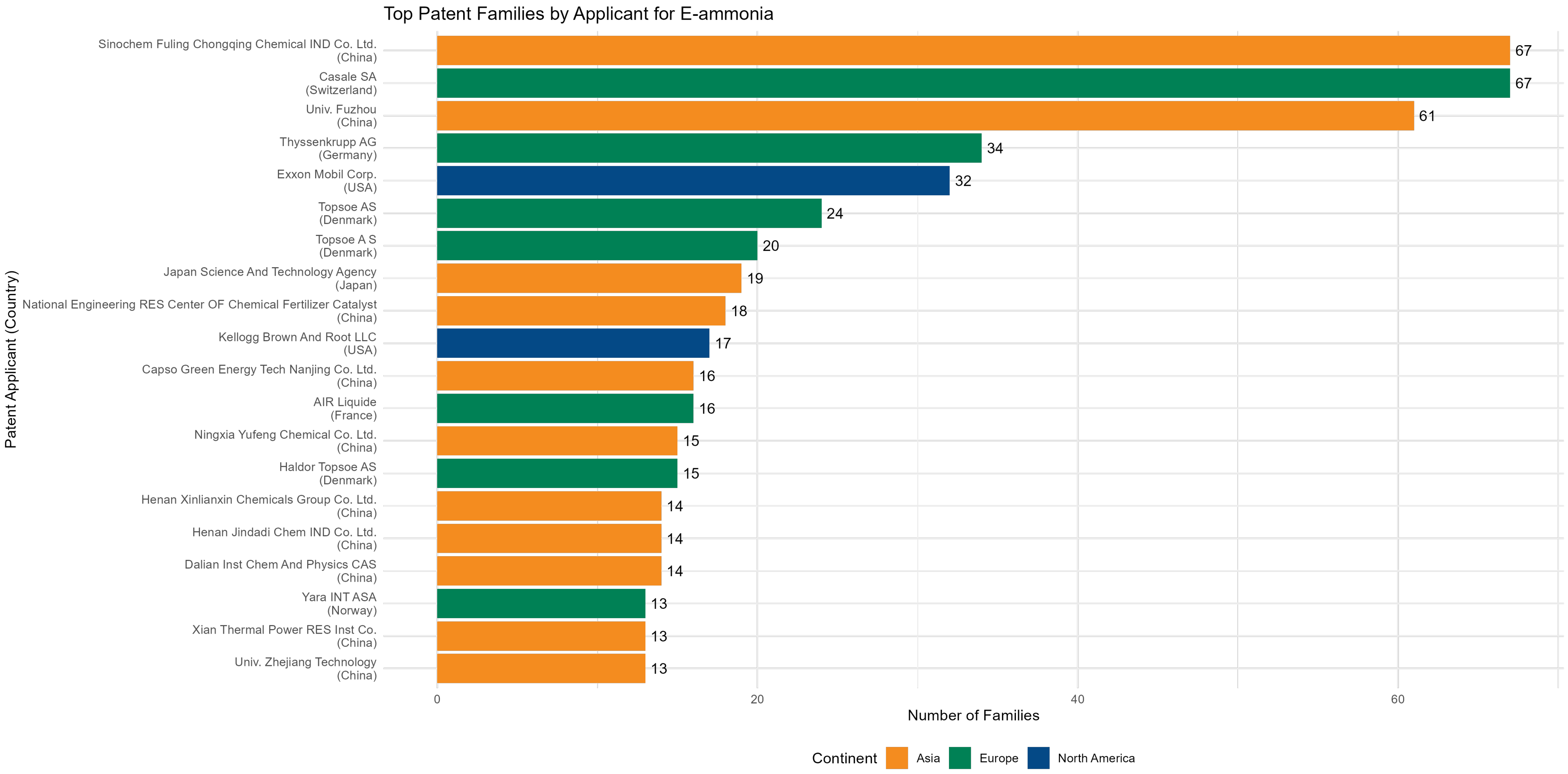
Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 2824

Emerging lowly promising technology

E-Ammonia

World actors

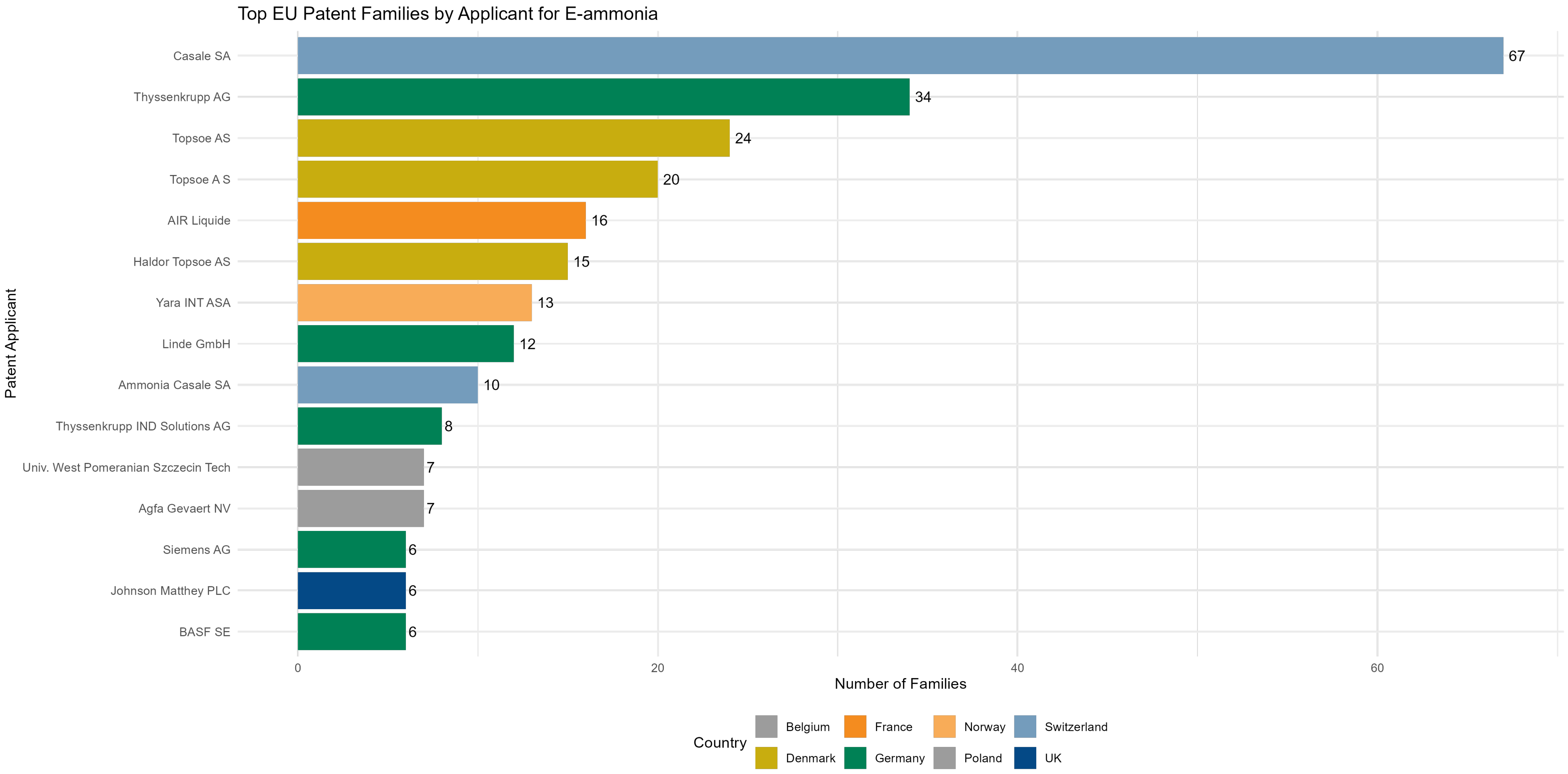


Fraunhofer INT

Emerging lowly promising technology

E-Ammonia

Europe actors



Fraunhofer INT

Compressed Air Energy Storage (CAES)

Search

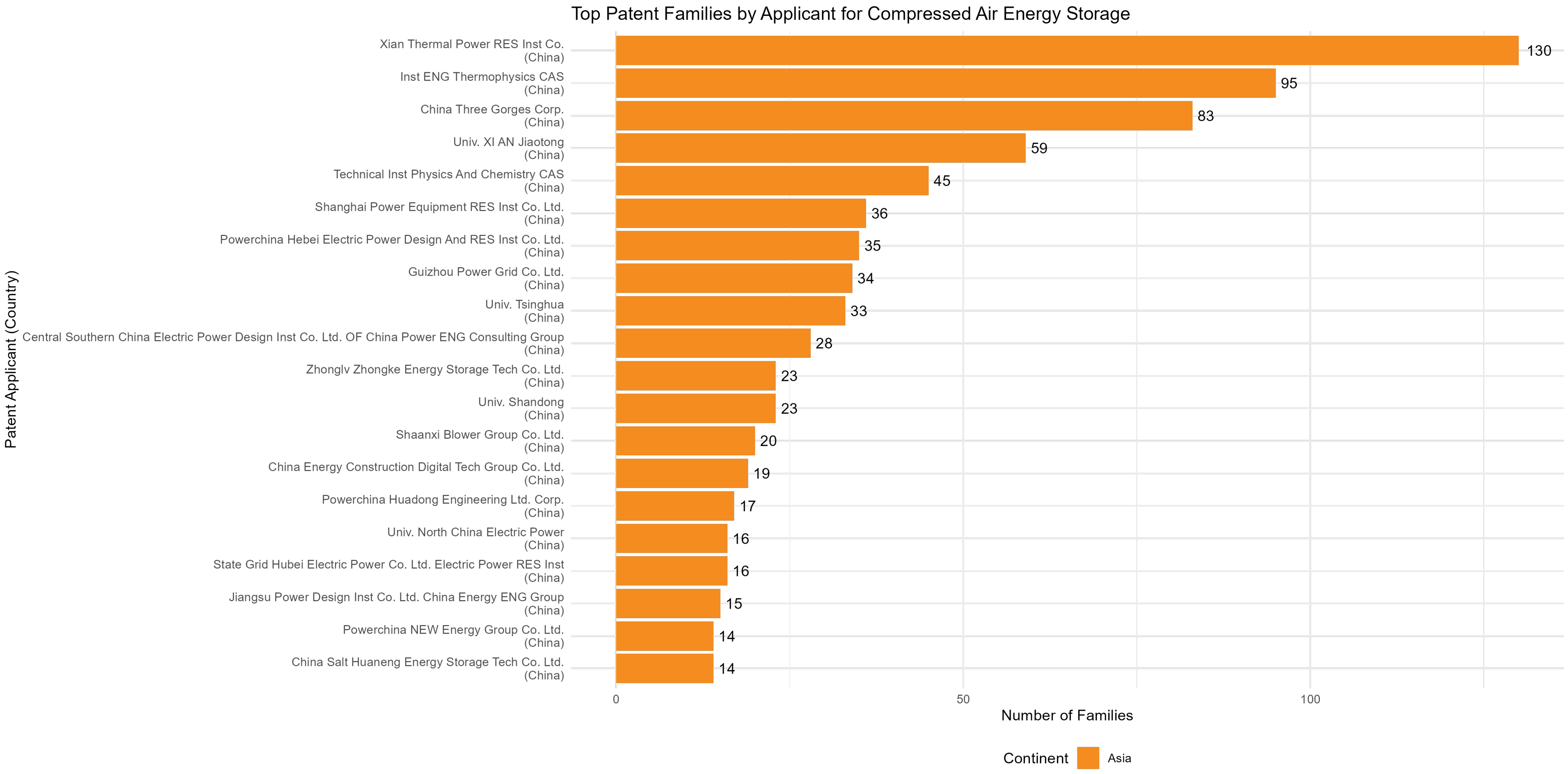
Search Query: SPUB=((TAC=(**CAES**) AND CPC=(**Y02E60/16**)) OR TAC=(("**compressed air energy storage**" AND ("**system**" OR "**renewable energ***")) OR "**Supercritical CAES**" OR "**Underwater CAES**" OR "**Liquid Air Energy Storage**") AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 2034

Compressed Air Energy Storage (CAES)

World actors

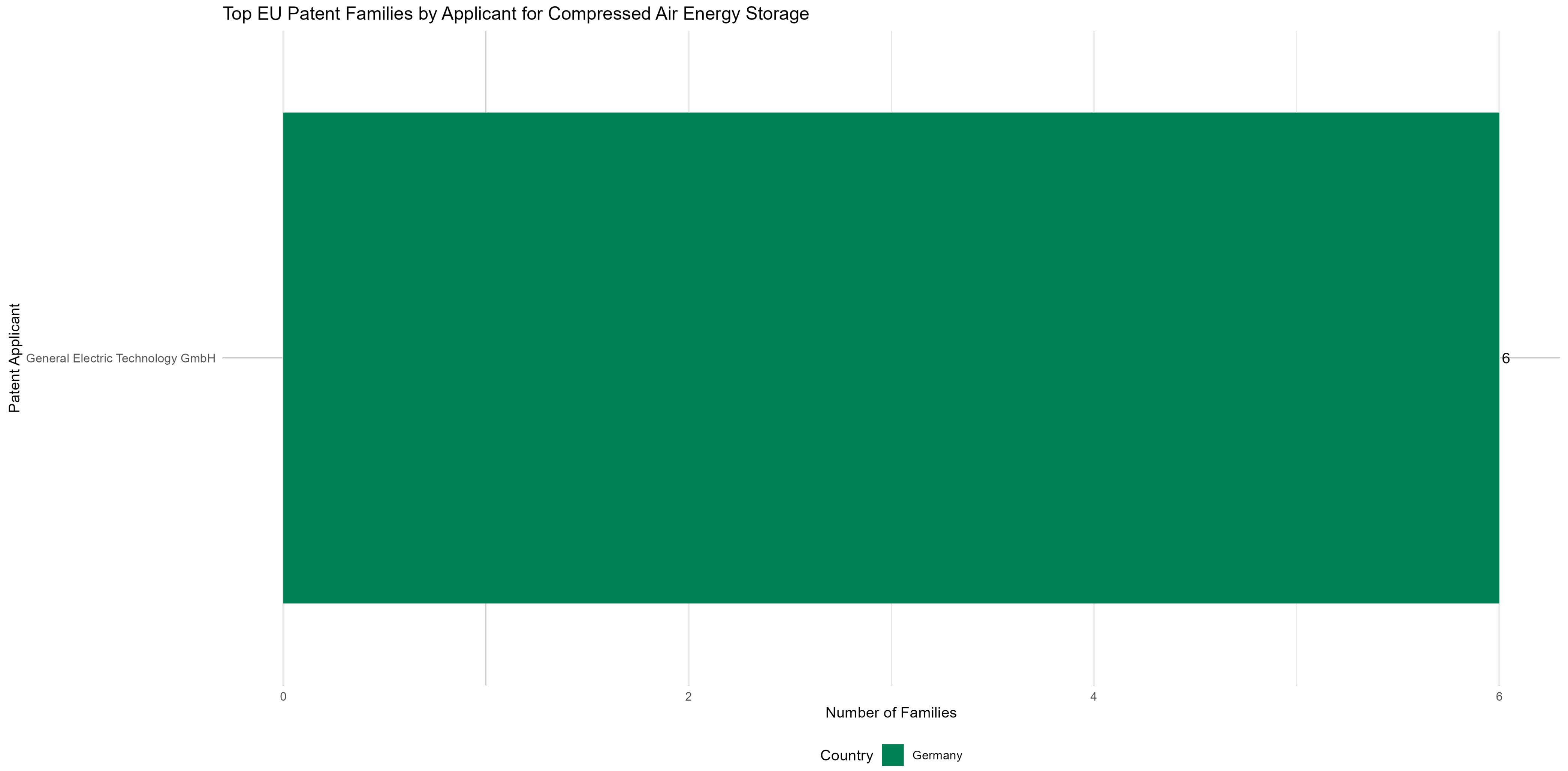


 15.09.2025

Fraunhofer INT

Compressed Air Energy Storage (CAES)

Europe actors



Emerging lowly promising technology

Supercapacitors

Search

Search Query: SPUB=(TAC=("**supercapacitor***" OR "**ultracapacitor***" OR "**electrochemical capacitor***")

AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

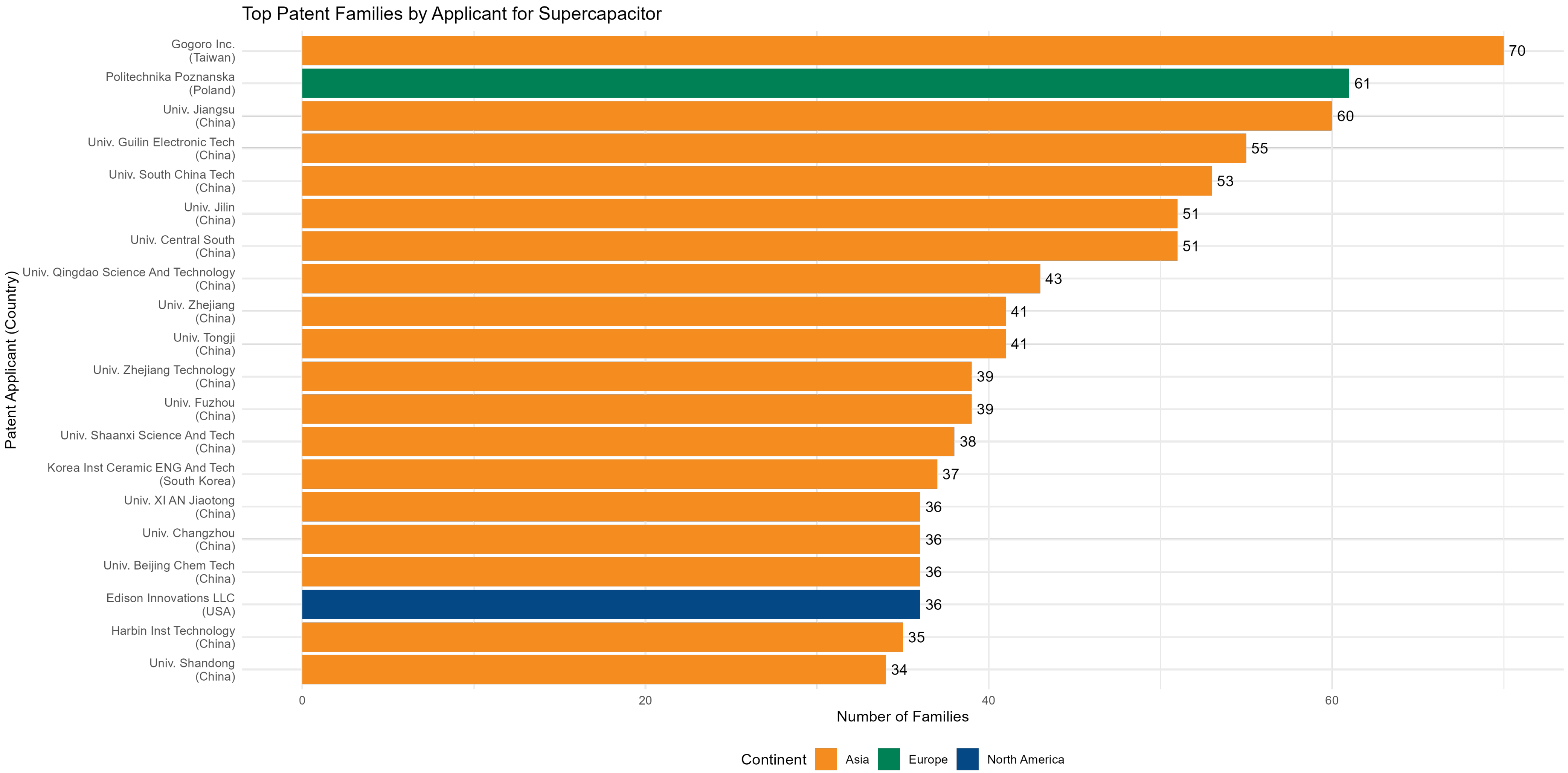
Patentfamilies: 11391

Fraunhofer INT

Emerging lowly promising technology

Supercapacitors

World actors

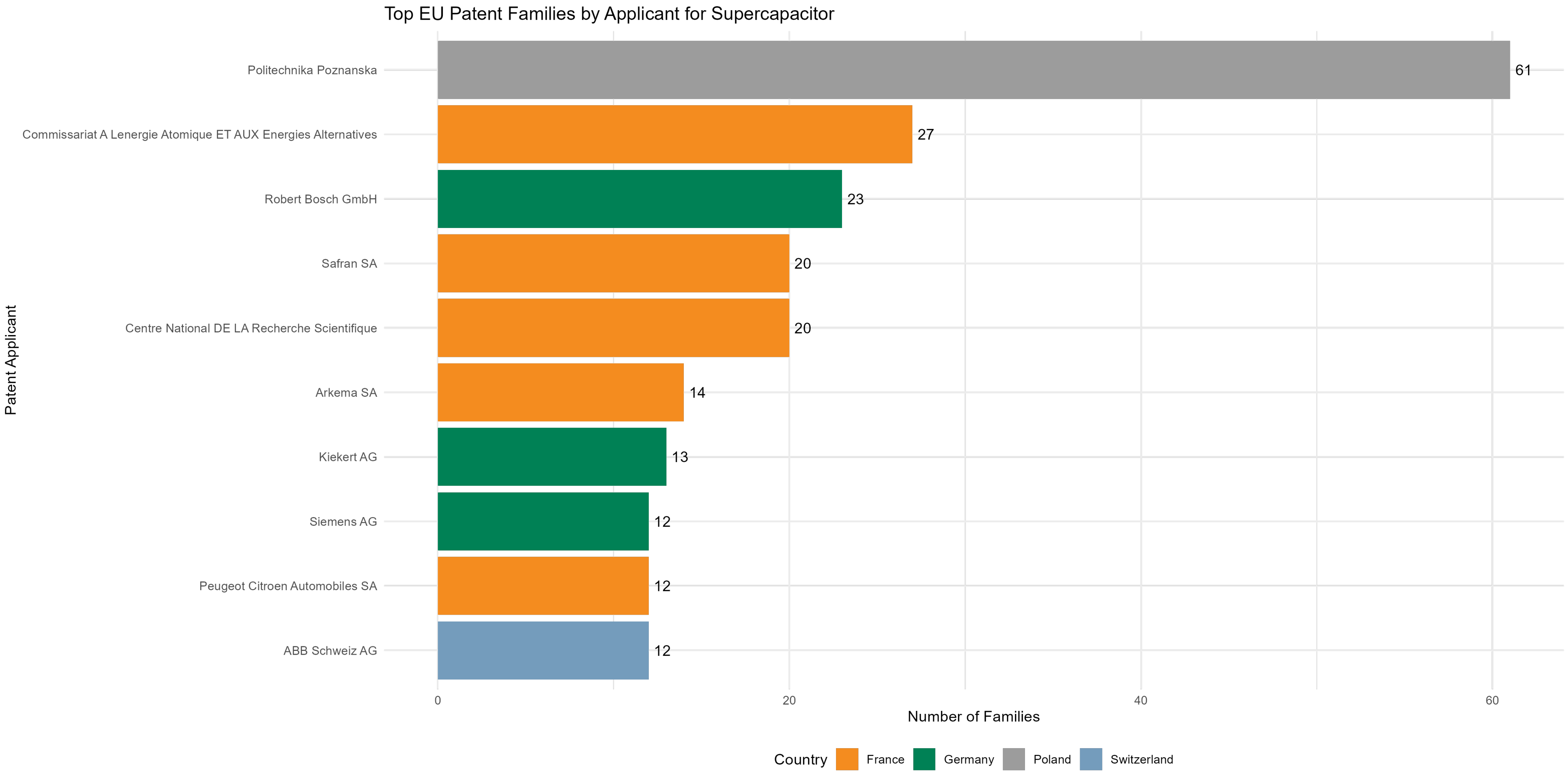


Fraunhofer INT

Emerging lowly promising technology

Supercapacitors

Europe actors



Fraunhofer INT

Emerging lowly promising technology

Carnot Batteries

Search

Search Query: SPUB=(TAC=("**Carnot batter***" OR "**thermal energy storage batter***" OR "**Thermal energy batter***") AND ALIVE=(YES))

Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

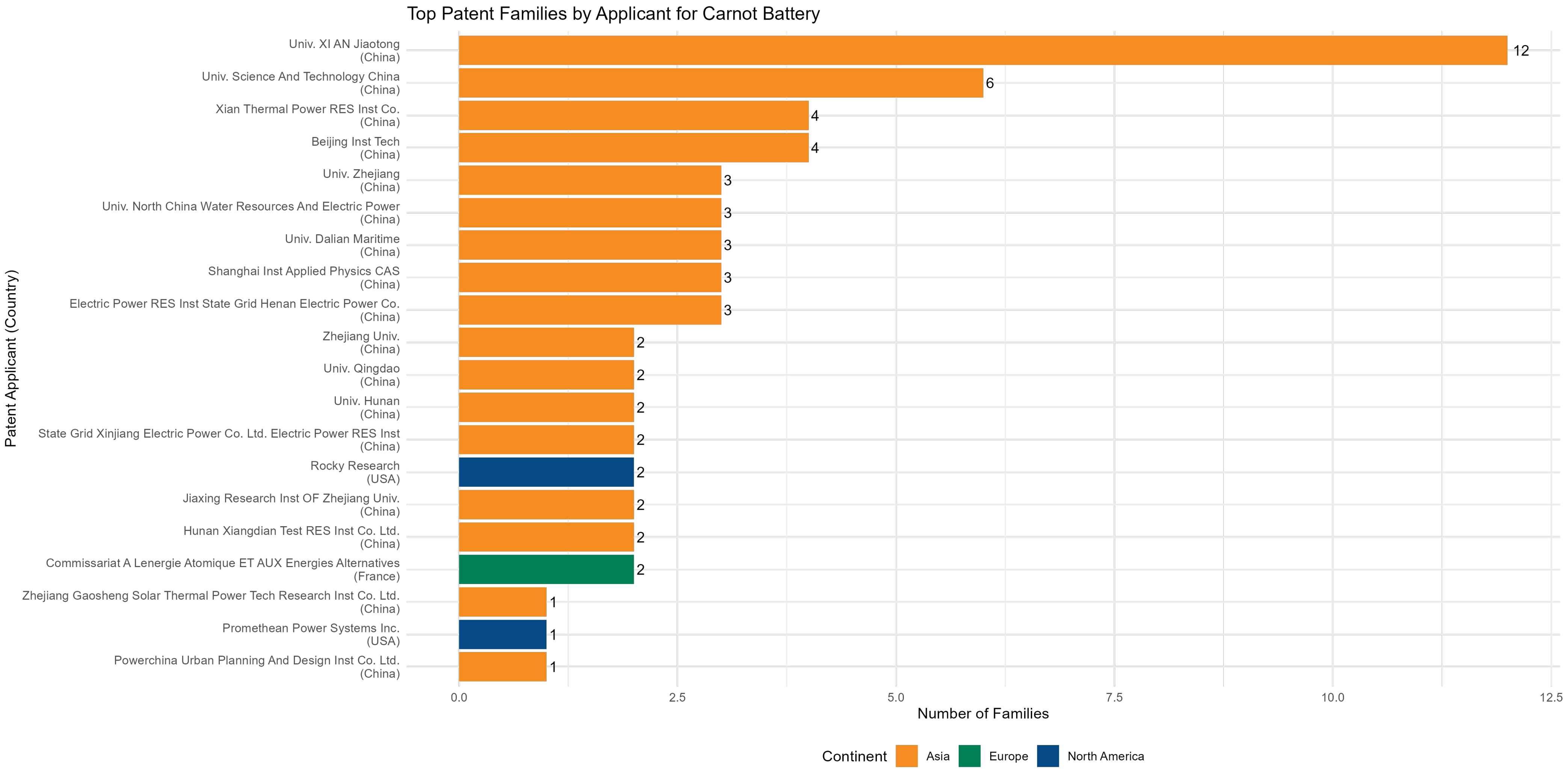
Patentfamilies: 102

Fraunhofer INT

Emerging lowly promising technology

Carnot Batteries

World actors

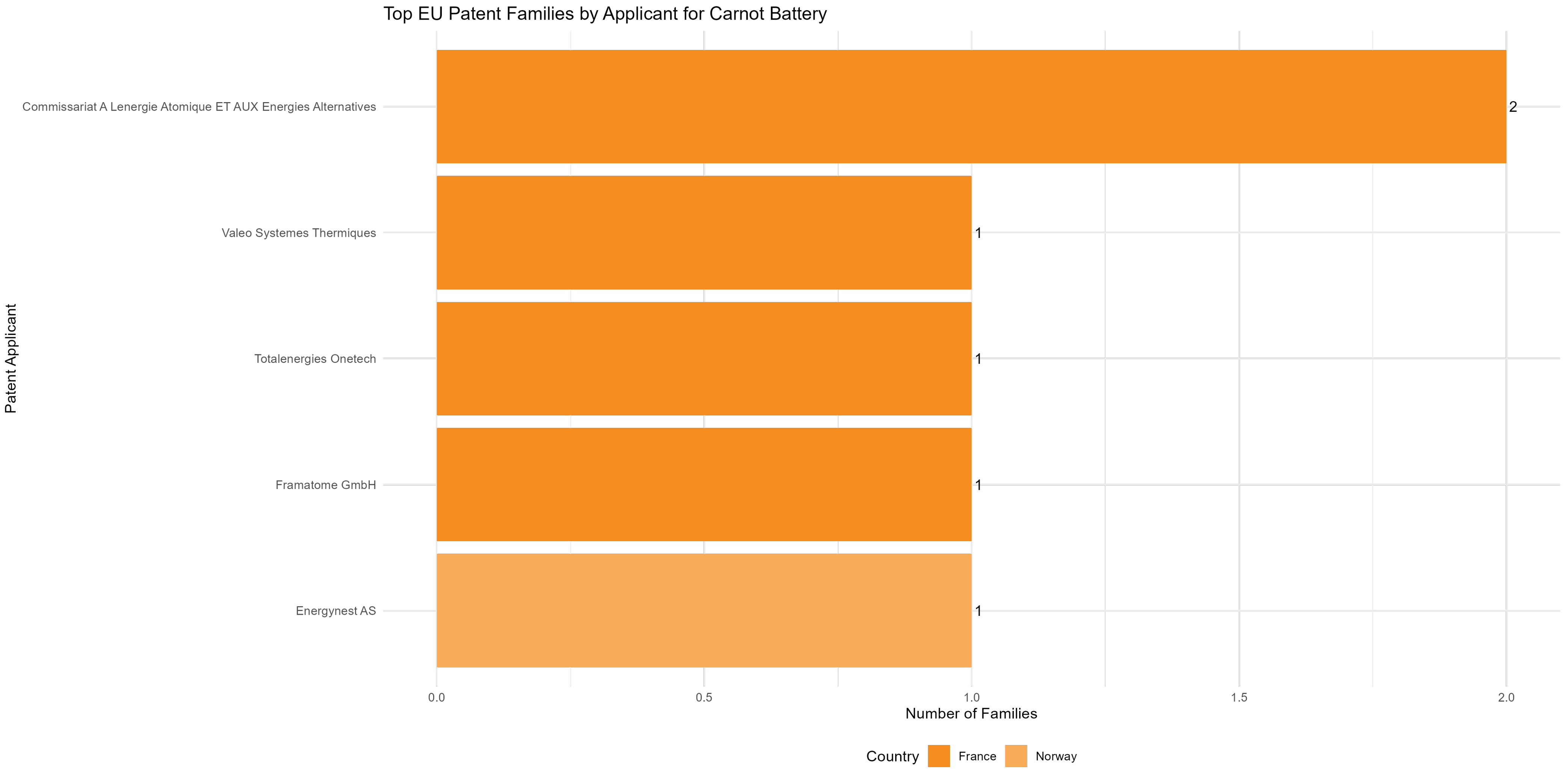


Fraunhofer INT

Emerging lowly promising technology

Carnot Batteries

Europe actors



Fraunhofer INT

Emerging lowly promising technology

Flywheel (mechanical energy storage)

Search

Search Query: SPUB=((TAC=("**Flywheel Energy Storage**")

OR (TAC="**flywheel**" AND CPC=(**Y02E60/16**)))

AND ALIVE=(YES))

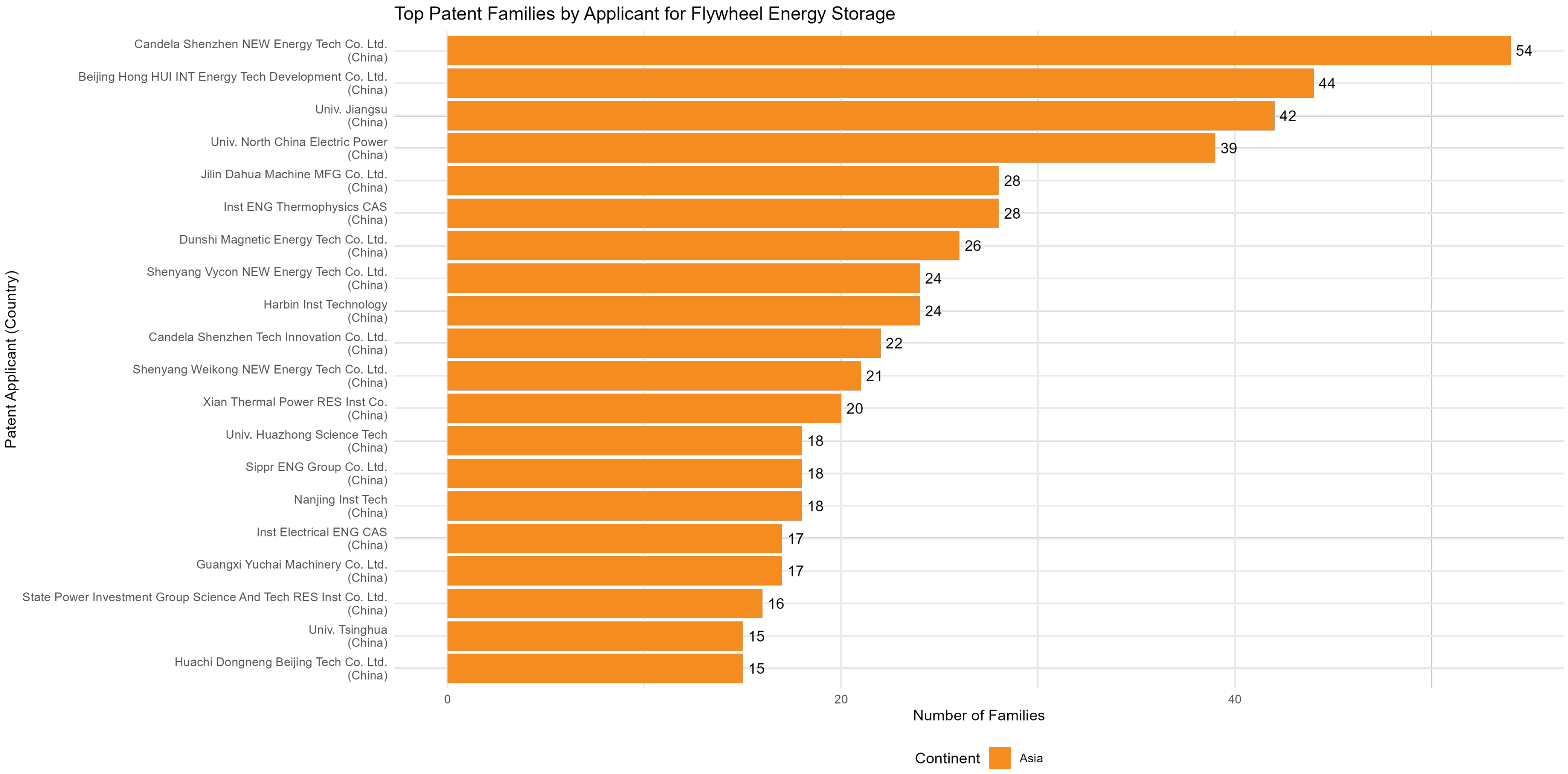
Used abbreviations in the search query: SPUB = Same Publication, a patent document must meet all criteria of the search query; TAC = Search in Title, Abstract, Claim; IC8 = IPC Class; CPC = CPC Class; ALIVE = Patent is active.

Patentfamilies: 3055

Emerging lowly promising technology

Flywheel (mechanical energy storage)

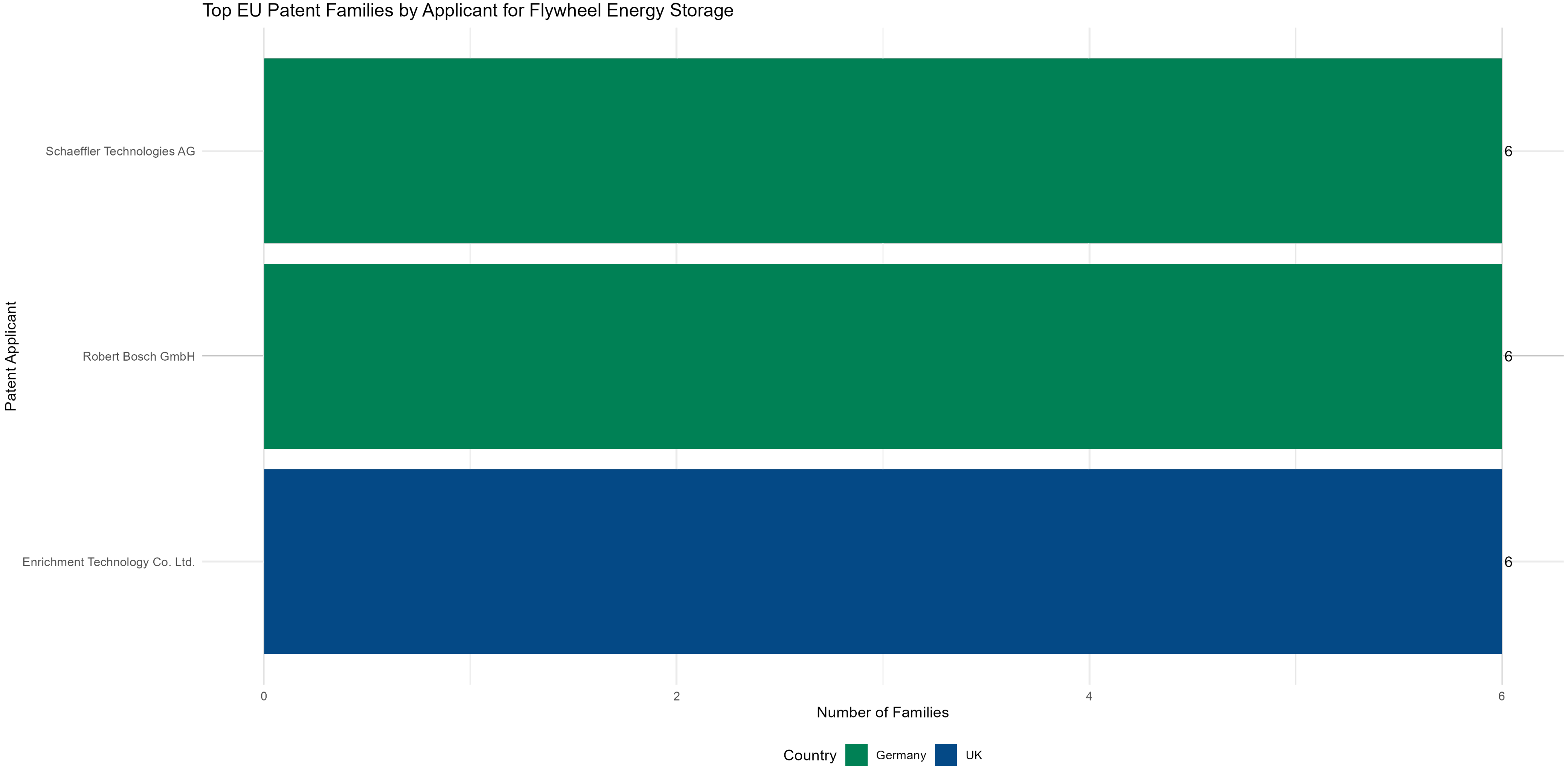
World actors



Fraunhofer INT

Flywheel (mechanical energy storage)

Europe actors



Annex 2 – Technology and Survey Product Tiering

Disclaimer

The following tables provide an indicative mapping of technologies (fact sheets) and products (survey responses) into four tiers. This mapping is based on a qualitative assessment of reported or documented compliance with the functional and technical requirements defined in Deliverable 2.3.
The classification does not represent an endorsement or rejection of any technology or provider. It serves solely to document the analytical process conducted in the SOTA phase. Final validation will be carried out in subsequent PCP steps (requirement weighting, clarification rounds, structured end-user testing).

Table 1: Technology Clusters (Fact Sheets, n = 33)

Tier 1 – Core COTS candidates	Tier 2 – Niche / Contextual	Tier 3 – Emerging Promising	Tier 4 – Horizon Scanning
Crystalline Silicon PV	Small Hydro	Sodium-Ion Batteries	Wave Energy Converters
Thin-Film PV	Small Wind	Solid-State Batteries	Solid-State Wind
Lithium-Ion Batteries	Flow Batteries	Metal Hydrides (H2)	Airborne Wind
Hydrogen Fuel Cells (PEM)	Micro Gas Turbines	Perovskite & Tandem Solar Cells	Compressed Air Energy Storage
Electrolyzers (H2)	Biomass & Waste-to-Energy	Lithium-Sulphur Batteries	Supercapacitors
Methanol-Based Energy Systems		Metal-Air Batteries	Carnot Batteries
		Hydrogen-Fueled ICEs	Flywheel Energy Storage
			LOHCs
			Ammonia
			Tidal Energy
			Small Modular Reactors
			Pedal-Powered Generators
			E-Fuels

Table 2: Survey Products (Anonymised, n = 24)

Tier 1 – Core COTS candidates	Tier 2 – Niche / Contextual	Tier 3 – Emerging Promising	Tier 4 – Horizon Scanning
Technology 1	Technology 5	Technology 13	Technology 23
Technology 2	Technology 9	Technology 14	Technology 24
Technology 3	Technology 10	Technology 21	
Technology 4	Technology 11		
Technology 6	Technology 12		
Technology 7	Technology 15		
Technology 8	Technology 16		
Technology 17	Technology 19		
Technology 18	Technology 22		
Technology 20			