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State of LDES

A Report on the Future of Long-Duration Energy Storage

MAY 2024

Jard van Ingen
Rajvardhan Desai

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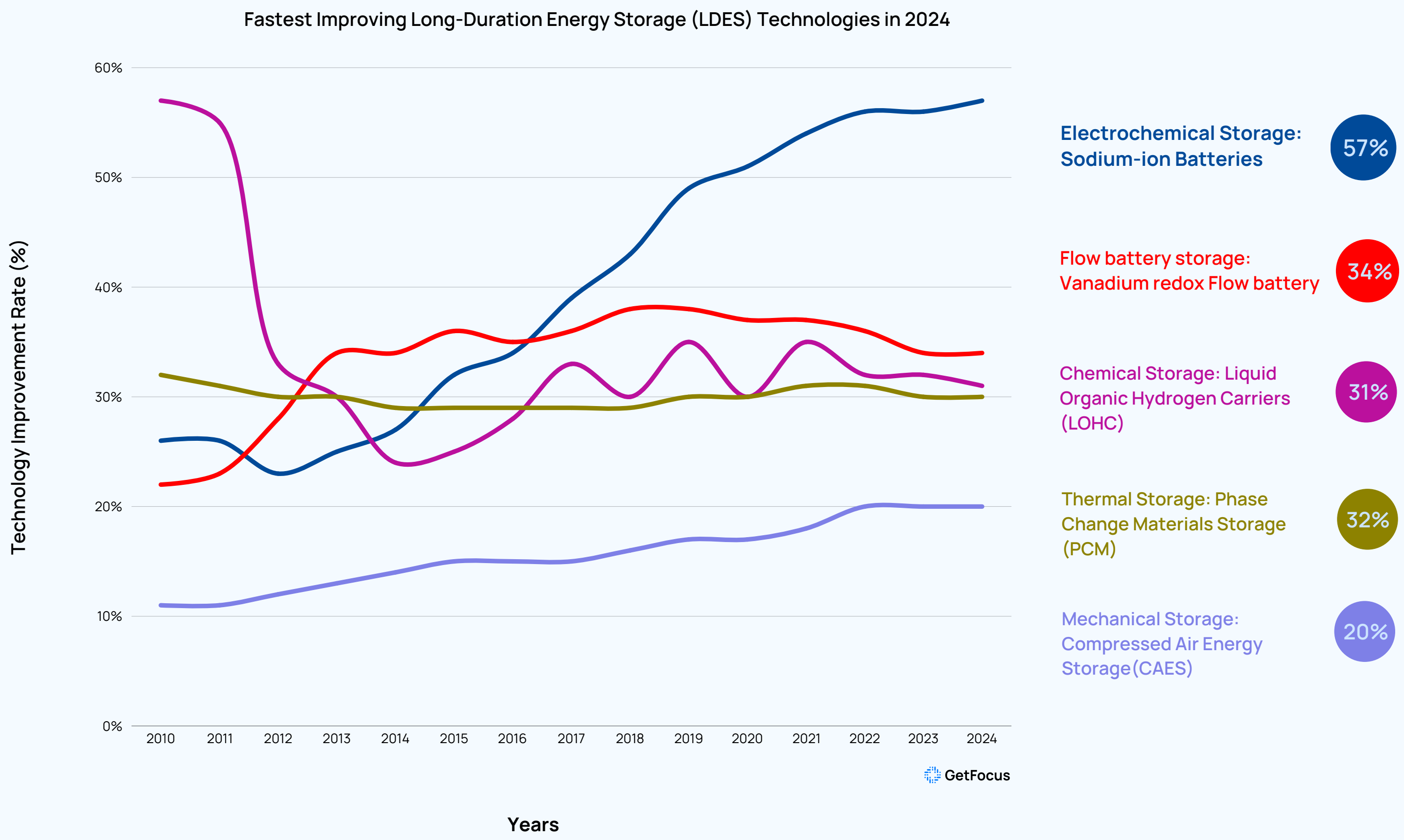
Many Long-duration Energy storage technologies will coexist, but which will lead?

We are witnessing a move towards renewable energy, but its intermittent nature (such as solar and wind's dependence on weather conditions) calls for effective energy storage solutions. Long-duration energy storage (LDES) technologies are pivotal, designed to store energy for extended periods and deliver it during energy deficits, thus supporting the integration of renewables and enhancing grid stability.



Graph 1: Fastest Improving Long-Duration Energy Storage Technologies (LDES) in 2024

Many LDES technologies are being developed, each with different features and uses. In this study, about 30 of them have been studied in detail. Out of these, we selected the fastest-improving LDES technologies in 2024 in each category and assessed them by their utility characteristics to find the most versatile technology set to revolutionize Long-Duration Energy Storage.

Major Findings:

1 Sodium-Ion Batteries For the Win (TRL 7)

Looking ahead to 2028, Sodium-ion Batteries are expected to take a leading role in the LDES market. They are not only cost-effective compared to lithium-ion batteries but are also improving at the fastest rate among all LDES technologies, with a remarkable improvement rate of 56% in 2024. The primary hurdles for sodium-ion technology are enhancing energy density and round-trip efficiency, with ongoing developments also aimed at increasing their longevity and lifecycle performance.

2 Vanadium Redox Flow Batteries for energy storage at the grid (TRL 8)

In 2024, these batteries show an improvement rate of 34%. They have a long lifecycle, require little maintenance, and can adjust their energy storage and power output levels independently making them suitable for both utility-scale(kWh) and large-scale(MWh) power management. However, their initial setup is expensive due to complex systems and larger footprint/infrastructure requirements (owing to a lower energy density) compared to electrochemical batteries like Sodium-ion. These challenges are currently a subject of ongoing research.

3 Compressed Air Energy Storage (CAES) maintains the relevance of Mechanical Energy Storage (TRL 7)

Characterized by their cost-efficiency over their lifecycle, Mechanical Energy Storage Technologies remain a preferred option for massive scale (Giga-Watt) long-duration energy storage for Front-of-the-Meter applications. Among mechanical storage methods, Compressed Air Energy Storage (CAES) technologies show the most significant improvement, with an improvement rate of 20% in 2024. Their most significant challenge is dependence on favorable geological conditions and cost competitiveness with upcoming battery technologies.

Introduction

In an era where our energy consumption has reached unprecedented levels, the challenge of meeting this demand with sustainable practices is more pressing than ever. Energy generation has hit historic highs, yet it struggles to keep pace with our growing needs. The discourse around energy generation and supply has become a central issue within government quarters as well as commercial sectors, highlighting its significance in our current times.

Moreover, the Paris Agreement has catalyzed a shift towards renewable energy sources, driving both governments and private institutions towards greener alternatives. Despite the rapid growth in renewable energy adoption, our reliance on these sources remains constrained by their inherent intermittency— it isn't always sunny or windy, leading to periods of energy shortfall. This underscores the crucial need for energy storage solutions that can bridge the gap between generation and demand, even when renewable sources are not producing at their peak.

Enter "Long-duration energy storage (LDES)" technologies, designed to store energy for extended periods—ranging from hours to months—thus ensuring a steady supply when needed.

The role of Long-duration energy storage (LDES) is twofold: Firstly, they facilitate the integration of renewable energy by storing excess power generated during optimal conditions and deploying it during off-peak times, thus mitigating the intermittency issue. Secondly, they enhance grid reliability and resilience, ensuring a balanced supply and demand over longer durations, which is vital for stabilizing the grid against disruptions.

Global initiatives, including the EU's comprehensive energy storage recommendations in March 2023 and the US Inflation Reduction Act of 2022, which earmarks $370 billion for clean energy, underscore the growing importance and demand for LDES technologies. This momentum towards renewable energy sources highlights LDES's importance.

However, the deployment of LDES technologies, as per institutional reports, faces several challenges:

- cost competitiveness with traditional and other renewable energy storage methods;
- efficiency in minimizing energy loss during storage and retrieval;
- scalability to accommodate large grid demands; and
- minimal environmental impact concerning safety, land use, and resource depletion.

Moreover, these technologies must align with the utility characteristics of an energy grid — fluctuating supply demand; offering simultaneous storage and supply capabilities; and varying applications (Front-of-the-meter and Behind-the-Meter) — energy generation sites, central distribution stations, and end-use locations.

The LDES landscape features a variety of long-duration energy storage (LDES) technologies, each designed for specific needs and contexts. As the field of energy storage evolves rapidly, understanding the shifts is crucial.

In this report, we identify the fastest-improving LDES technologies in each category, based on fundamental energy storage principles. Fastest improving technologies typically disrupt the market and we therefore evaluate their utility to determine how each technology fits into the LDES puzzle and explore whether there is a 'wildcard'—a versatile technology that meets all LDES needs under any scenario.

Technology Forecasting: What Is It, and How Does It Work?

Inventors worldwide are constantly pushing the boundaries of technology, which in turn creates a massive data trail that can be mined for all sorts of insights.

The key thing here is that before new generations of technology hit the market, they are already described in the patent literature. If done well, patent data allows us to take a peek at the future.

At GetFocus, we developed a quantitative method to forecast the technological future based on metrics that can be identified in patent data. Using the latest advancements in AI technology, we have created a system that can estimate how rapidly any area of technology is improving.

Our method revolves around 3 key steps.

1. We identify every single patent that relates to an area of technology using AI. The resulting dataset represents the entire developmental history of an area of technology.
2. Once this data set is created we measure 2 key metrics[1].

    a. Cycle Time - How many years it takes for a technology to produce a new generation of itself.

    b. Knowledge Flow - How significant of a step forward a new generation represents.

[1] Reach out to us if you are interested in learning more about our proprietary metrics.

3. Using the above metrics, we calculate the 'Technology Improvement Rate', which represents the average percentage (%) increase in performance per dollar that can be expected from an area of technology in one year.

By using the above methodology, technology improvement speeds can be accurately measured, and those speeds can be used to predict technological disruption well ahead of time.

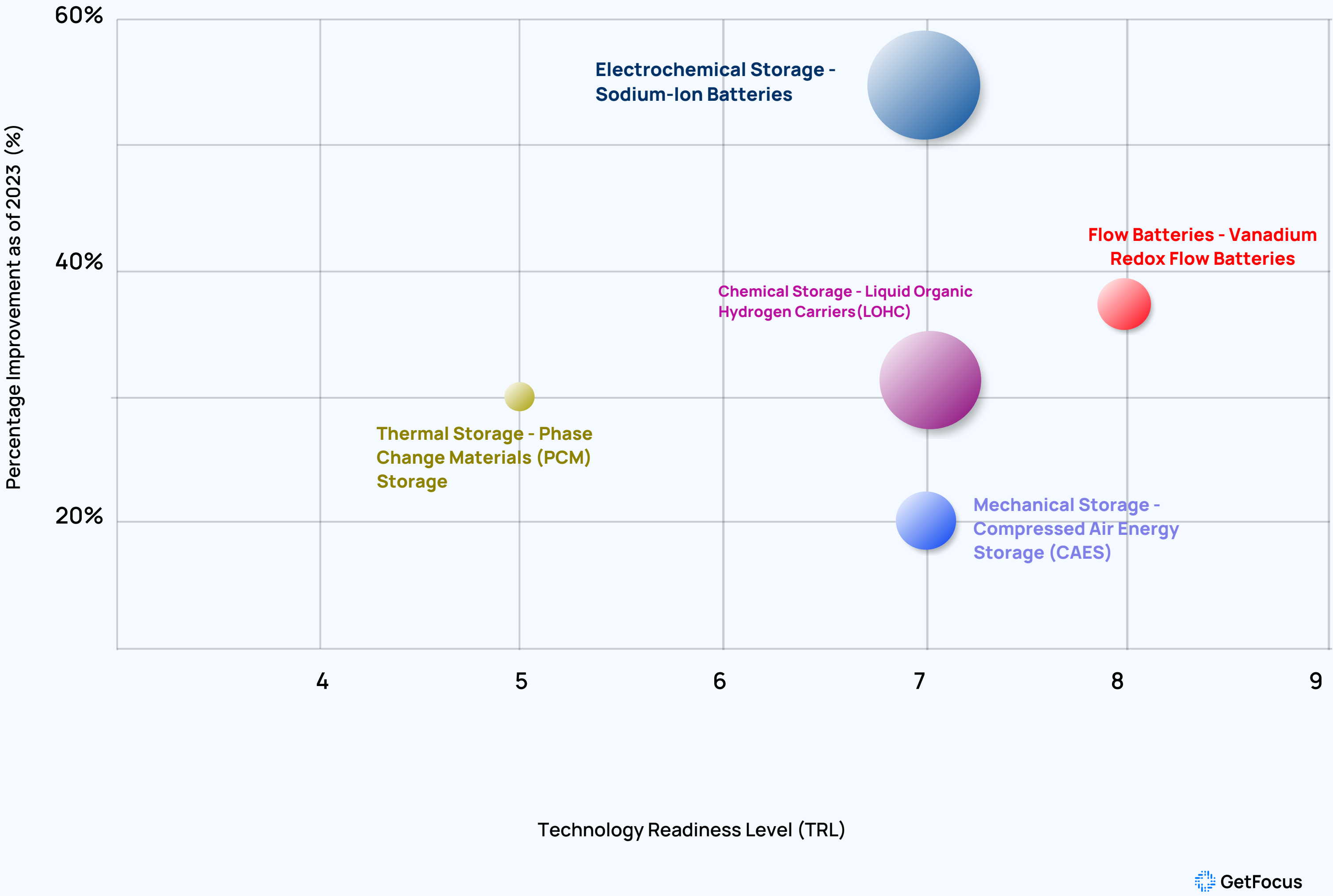
If GetFocus and our method had been around in the past, one could have known that:

- Lithium-ion batteries would eventually become cheaper than combustion engines for vehicles by 1995,
- Digital photography would disrupt film by 1975,
- SSDs would become cheaper than HDDs by the early '80s, and the list goes on and on.

All in all, our forecasting method has been verified on more than 150 technological areas.

Which Long-Duration Energy Storage (LDES) Technology is Improving the Fastest?

We reviewed a total of thirty technologies. Using our method, we picked the fastest improving ones. Since various long-duration energy storage (LDES) technologies will exist together, serving different needs and contexts, we chose the quickest advancing technology from each LDES category. These categories follow the basic principles of energy storage.



Graph 2: The fastest improving LDES technologies: Improvement Rate (%), Technology Readiness Level (TRL), and the number of Patent Families.

Summary of Analysis

Electrochemical Storage - Sodium-Ion Batteries (TRL 7)

Electrochemical long-duration energy storage (LDES) technologies, such as lithium-ion and sodium-ion batteries, convert electrical energy into chemical energy for storage and back to electrical energy when needed. These technologies are energy-dense, scalable, highly efficient, and boast long lifecycles, making them versatile for a wide range of applications. They easily integrate into the grid, enhancing stability and flexibility in energy management, and facilitating decentralized energy production and storage. Challenges include high initial costs, material and resource constraints, and environmental concerns regarding disposal.

The fastest improving technology within the electrochemical storage category is Sodium-ion batteries. They store energy by transferring sodium ions between electrodes during charge and discharge cycles. They offer cost advantages over lithium-ion batteries due to the abundance of sodium However, they have lower energy density and a shorter lifecycle compared to lithium-ion batteries. They are also the fastest-improving LDES technology overall in 2024, with an improvement rate of 56%.

Flow Batteries - Vanadium Redox Flow Batteries (TRL 8)

Flow batteries excel in stability and flexibility, allowing deep discharges without significant energy losses—ideal for integrating fluctuating renewable energy sources like solar and wind. Their unique design separates energy storage capacity (determined by electrolyte volume) from power capacity (determined by cell stack size), facilitating tailored applications. Despite their longer cycle life and scalability, they suffer from lower energy density and require larger spaces and more complex system designs. Within the Flow-batteries category both Vanadium and Zinc-Bromine Redox flow batteries are improving the fastest at equal rates and have similar characteristics. However, Bromine's toxic traits and thus higher safety and maintenance requirements limit their utility. We therefore select only Vanadium Redox Flow batteries for further assessment.

Vanadium Redox Flow Batteries use vanadium ions at varying oxidation states to store and release energy, combining high safety due to non-flammable electrolytes and moderate efficiency (70-80%). They are improving at 34% in 2024, making them the second fastest-improving LDES technology overall.

Chemical Storage - Liquid Organic Hydrogen Carriers(LOHC) (TRL 5)

Chemical storage technologies, including hydrogen, synthetic natural gas, and liquid air or ammonia, address renewable source intermittency by offering high energy density and scalability. These systems are generally less costly for extended periods (from several hours to months) but suffer from high conversion losses and substantial infrastructure needs.

The fastest improving technology in the chemical storage category is Liquid Organic Hydrogen Carriers(LOHC). LOHC systems bind hydrogen to organic compounds, creating stable, non-toxic, transportable liquids. These systems are highly energy-dense and safe, but releasing hydrogen requires significant heat, leading to efficiency losses. LOHC is improving with a 31% improvement rate in 2024, offering substantial decarbonization potential across various renewable sources.

Thermal Storage - Phase Change Materials (PCM) Storage (TRL 7)

Thermal storage systems use materials like water, molten salts, sand, or phase change materials (PCMs) to store heat, which can later be converted back to electricity or used for heating or cooling. These systems are inherently capable of storing large amounts of energy cost-effectively for extended periods (several weeks) and are highly flexible for both heating and electricity generation on a grid scale. However, they are limited by conversion losses typical of thermodynamic cycles.

Phase Change Materials (PCM) are improving the fastest in the Thermal Storage Category. PCMs store thermal energy through the melting and freezing processes, releasing or absorbing heat at consistent temperatures. These materials are improving at 30% in 2024, offering promising solutions for efficient energy retrieval.

Mechanical Storage - Compressed Air Energy Storage (CAES) - TRL 7

Mechanical storage technologies convert electrical energy into various forms of physical energy (e.g., pumped hydro, compressed air, kinetic energy). These traditional technologies are proven for large-scale energy storage (in the scale of hundreds of Mega-watts and even Giga-watts) but are often geographically and financially constrained, limiting their suitability for urban or residential settings.

The fastest improving technology within the mechanical storage category is Compressed Air Energy Storage (CAES). CAES systems compress air and store it in underground reservoirs, with energy released by heating and expanding air through turbines to generate electricity. With efficiencies over 75% and capabilities for large-scale and instant power supply, CAES is improving at 20% in 2024.

Evaluating the Fastest Improving Long-Duration Energy Storage Technologies: Utility Characteristics and Application

Table 1: Evaluating Fastest Improving LDES Technologies for their Utility Characteristics

Legend	0: Unsuitable	1: Not well suited	2: Medium Suitability	3: Well Suited	
	Long-Duration Energy Storage Technologies				
Utility Characteristics	Sodium-ion Batteries	Vanadium redox Flow Batteries	Phase Change Materials (PCM) storage	Liquid Organic Hydrogen Carriers (LOHC) storage	Compressed Air Energy Storage (CAES)
Compliance with fluctuating supply-demand	2	3	1	0	3
Simultaneous storage and supply capabilities	3	3	1	1	2
Operating capability at the energy generation site	3	3	2	2	3
Operating capability at the central distribution station	2	3	1	2	3
Operating capability at end-use sites (e.g. buildings)	3	2	3	1	0
Cost per unit of energy stored	2	1	2	1	3
Round-trip efficiency	3	2	1	1	2
Scalability	2	3	1	2	3
Environmental Impact	2	2	3	1	2
Suitability for storage of 10 MWh	2	3	1	2	3
Suitability for storage of 100 MWh	2	3	1	2	3
Suitability for storage of 10 GWh	1	2	1	2	3
Average Suitability	2.3	2.5	1.5	1.4	2.5

Sodium-Ion Batteries

Sodium-ion battery technology, less developed than lithium-ion, shows promise for long-duration energy storage due to its rapid improvement rate. Its main challenge is scalability—its lower energy density requires more units for large-scale storage in the mega or gigawatt-hour range compared to mechanical solutions like compressed air energy storage (CAES). Despite this, sodium-ion batteries are more efficient in round-trip energy use and offer greater operational flexibility, with less energy loss during storage and supply. The high improvement rate if attributed to improvements in energy density thereby reducing cost per unit of stored energy will position these batteries as a versatile solution across the energy grid— even for Mega-watt scale storage applications.

Vanadium Redox Flow Batteries

The major drawback of vanadium redox flow batteries is the high cost per unit of stored energy, driven by extensive infrastructure requirements and the need for high-purity vanadium. Enhancements in vanadium recycling and energy density could mitigate these costs and spatial demands. Although suitable for grid sites, the substantial infrastructure footprint may limit their attractiveness at end-use locations. The improvement rate if attributed to improving efficiency and energy density (reducing space and infrastructure needs) will make them a viable alternative for long-duration energy storage across the grid.

Phase Change Material Storage (PCM)

PCM storage technology currently falls short on several utility characteristics, primarily due to the extensive time and specific conditions needed for energy storage and retrieval. While PCM systems require less space, making them suitable for end-use applications, their low round-trip efficiency is a significant obstacle to widespread adoption. Advancements in efficiency and scaling storage capabilities to the megawatt-hour range are crucial. High costs, material compatibility, and integration challenges also hinder their practical application. If the improvement rate is attributed to increasing round-trip efficiency and scalability, PCM storage solutions can soon serve as an alternative for energy storage near the generation sites.

Liquid Organic Hydrogen Storage (LOHC)
LOHC technologies offer higher energy density and the potential to utilize existing liquid fuel infrastructure, which is a major advantage over traditional hydrogen storage methods. Challenges include efficiency losses during the hydrogenation/dehydrogenation cycle, slow ignition times impacting energy supply, and high operational costs. Development efforts focusing on catalysts to improve efficiency and reduce ignition delays are critical. The improvement rate if attributed to overcoming efficiency and cost, LOHC could become a compelling substitute for conventional small-scale power generators like those powered by diesel.

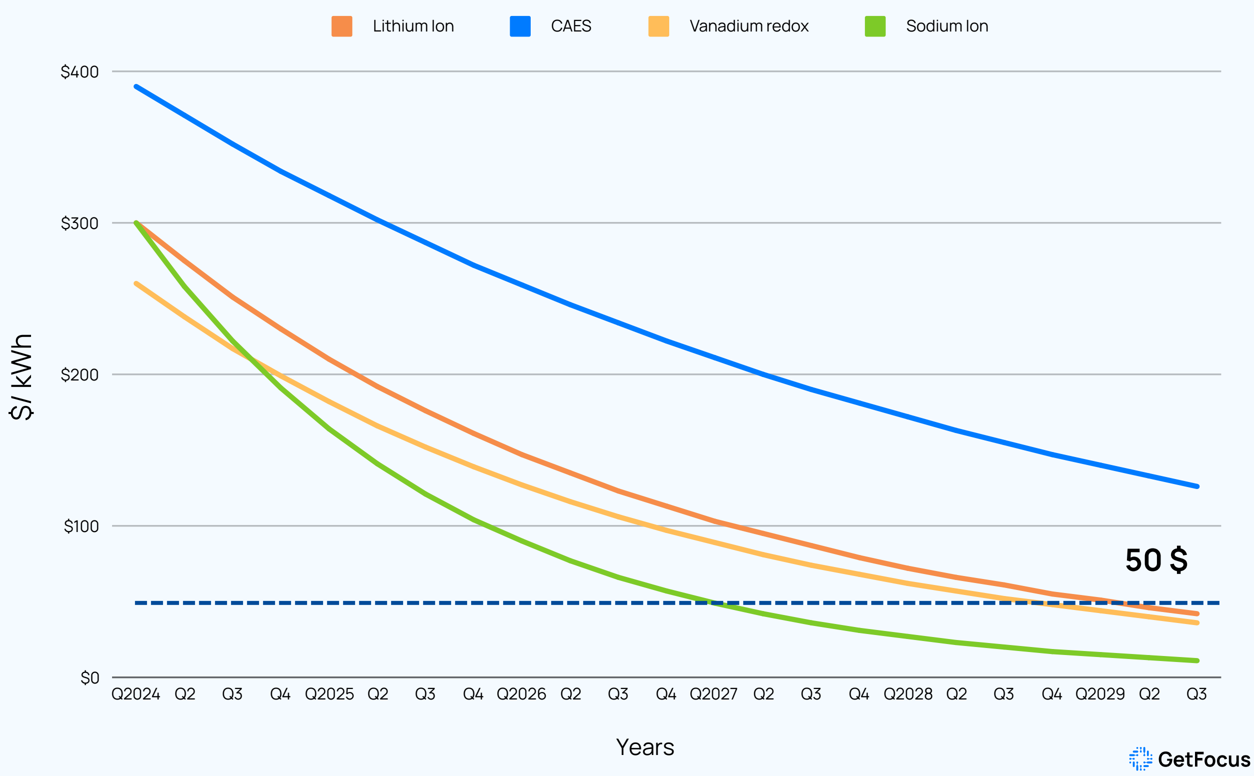
Compressed Air Energy Storage (CAES)
CAES is known for its scalability, reliability, and potential to minimize environmental impacts when integrated with renewable energy sources. Despite these advantages, CAES systems must meet specific geological conditions, entail high initial investments, and generally offer lower round-trip efficiency. Improvement rate if attributed to enhancing efficiency, will make CAES a promising option for energy storage near the generation site, enhancing grid stability and supporting the shift towards renewable energy.

Table 2: Summary of Suitable Applications for Each Technology

Legend	0: Unsuitable	1: Not well suited	2: Medium Suitability		3: Well Suited
Technology	Sodium-ion Batteries	Vanadium redox Flow Batteries	Phase Change Materials (PCM) storage	Liquid Organic Hydrogen Carriers (LOHC) storage	Compressed Air Energy Storage (CAES)
Front of the Meter ApplicationSuitability Score (e.g. energy generation site, distribution station)	2	3	1	1	3
Reason	Can be used to regulate daily load variations and provide energy during peak demand periods.	Ideal for large-scale renewable integration, providing stable power over extended times.	Can be integrated with solar power plants but is less typical for direct front-of-the-meter usage.	Mainly used for transportation and industrial process sectors.	Highly Suitable for massive energy storage, smoothing out electricity supply from wind and solar farms.
Behind the Meter Application Suitability Score (e.g. Consumer applications)	2	1	2	1	0
Reason	Suitable for residential or small commercial energy storage due to their lower cost and decent energy density, providing backup power or peak-shaving.	Somewhat suitable for larger commercial or industrial facilities due to their scalability and long duration but requires significant space and maintenance.	Suitable for residential and commercial buildings for thermal energy storage, helping in heating and cooling management to reduce dependence on grid electricity during peak demand.	Somewhat suitable for industrial applications rather than residential due to the complexity and scale of infrastructure needed for hydrogen storage and release.	Unsuitable for behind-the-meter applications due to the large scale and geological requirements (e.g., underground caverns) necessary for implementation.

Forecasting

Sodium-ion batteries are quickly becoming a strong alternative for large-scale energy storage solutions, ideal for universal grid use.
To forecast which technology will lead the Battery energy storage system(BESS) based LDES in the future, we consider the costs of sodium-ion battery cells. In 2024, the average cost for sodium-ion cells is $87 per kWh[2] slightly cheaper than lithium-ion cells at $89 per kWh[3]. These costs reflect the average from various uses, including electric vehicles, and stationary storage.



Graph 3: Forecasting Costs of Sodium-ion and Lithium-ion Battery Cells.

2 Sodium-ion Batteries 2024-2034: Technology, Players, Markets, and Forecasts

3 BloombergNEF's annual battery price survey 2023

For GetFocus' forecasting method, we take into account the improvement speed of each of the above-mentioned technologies in 2024:

- Sodium-ion batteries: 56%
- Vanadium Redox Flow Batteries: 34%
- Compressed Air Energy Storage: 20%
- Lithium-Ion Batteries: 34%

According to the forecast, Sodium-ion BESS is expected to become more affordable than the other LDES technologies, reaching around **$50 per kWh by 2027**. Thus, making them viable for grid-level energy storage for renewable resources.

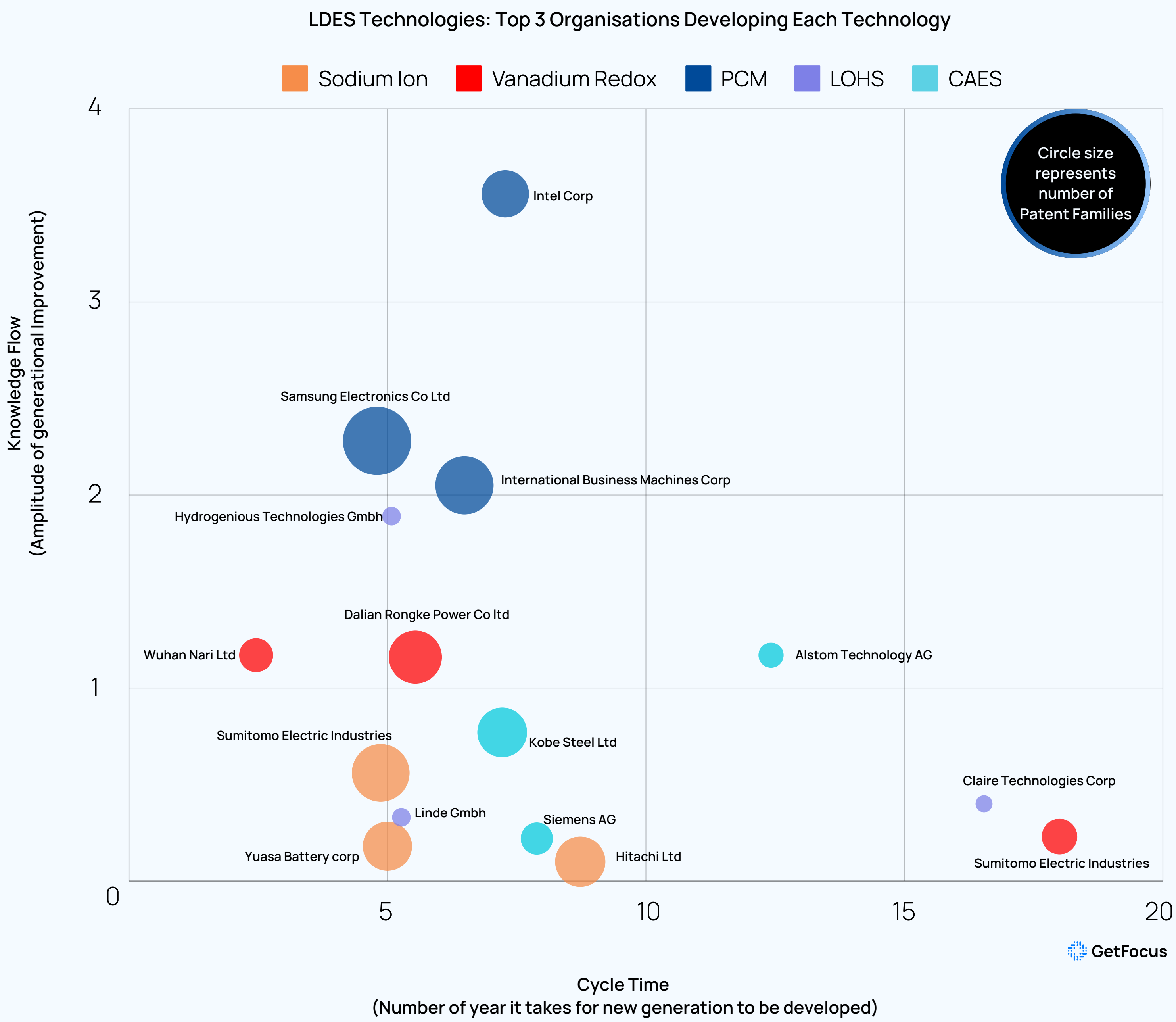
Our forecasting method is tied to the technology improvement rate, indicating that as technology advances, costs decrease.

While technological improvement is not the sole factor in cost reduction, it plays a crucial role. For instance, research shows that the sharp decline in Li-ion battery prices over the last 20 years is primarily due to new developments in materials and chemistry, rather than just economies of scale.

Approximately **38%** of the price drop is attributed to improvements in energy density. We are observing similar advancements with sodium-ion batteries and other LDES technologies. Given this similarity, we can expect their prices to decrease significantly, as illustrated in the graph.

At GetFocus, we have historical evidence that indicates a strong correlation between cost and performance of a technology. The technology improvement rate is a quantitative measure of technological improvement derived from patent data that directly translates to a technology's performance.

Which are the top 3 commercial organizations developing these fastest-improving technologies?



Graph: Top 3 Organisations Developing the fastest improving LDES technologies

- **Sodium-Ion Batteries**

Sumitomo Electric Industries Ltd., Hitachi Ltd., and Yuasa Battery Corp are leading the development in sodium-ion battery technologies. Although these companies have not yet commercialized their technologies yet, an announcement in 2023 by Great Power, a Chinese battery company, highlighted that a 50 MW/100 MWh Long Duration Energy Storage (LDES) project is in progress to power a data center, indicating serious consideration of sodium-ion batteries for long-duration energy storage.

- **Vanadium Redox Flow Batteries**

Dalian Rongke Power Co. Ltd., Sumitomo Electric Industries Ltd., and Wuhan Nari Ltd. are key players in the development and commercialization of vanadium redox flow batteries. Sumitomo Electric has been marketing these batteries since 2001, primarily to electric power companies. Notably, their batteries are set to be deployed at “Energy City-Kashiwazaki” in Japan, a leader in renewable energy production. Starting March 2024, the city plans to use a 1 MW x 8 hours flow battery unit from Sumitomo to enhance the adoption of renewable energies and stabilize the local power grid, boasting a lifespan of 20 years.

- **Phase Change Materials (PCM) Storage**

Prominent in the PCM storage sector are Samsung Electronics, IBM, and Intel Corp, all of which are major electronics manufacturers possibly leveraging their expertise in in-memory storage technologies. Conversely, Sunamp Ltd., based in Edinburgh, specializes in PCM with 10 patent families dedicated to LDES. Their product, the "Plentigrade P58" material-based PCM battery, claims a lifespan of 40,000 cycles without degradation. These compact batteries are designed to integrate seamlessly with solar panels, storing excess energy, and are particularly suited for behind-the-meter applications.

- L**iquid Organic Hydrogen Storage (LOHC)**

Linde GmbH, Claire Technologies Corp, and Hydrogenious Technologies lead the development of LOHC technologies. Founded in 2013, Hydrogenious Technologies has advanced the commercial application of LOHC in LDES, ranging from large-scale stationary storage linked to renewable energy sources to mobile applications like fuel cells in vehicles.

- **Compressed Air Energy Storage (CAES)**

Kobe Steel Ltd., Siemens AG, and Alstom AG are at the forefront of developing CAES technologies. Siemens AG, in collaboration with Corre Energy—a specialist in LDES—is innovating modular and scalable CAES solutions. This partnership is exploring the integration of hydrogen-powered compressed air energy storage (CAES) with renewable energy sources, showcasing the potential for synergies between multiple LDES technologies.

Conclusion

In this analysis, we have explored the fastest improving technologies across various categories of Long-duration Energy Storage Technologies (LDES) guided by the fundamental principles of energy storage. These technologies were evaluated based on the utility characteristics considered to be most important as per the latest institutional reports and technological roadmaps.

The fastest-advancing technology in the mechanical storage category is Compressed Air Energy Storage, which is best suited for front-of-the-meter applications. However, its deployment is limited by the need for specific geological formations.

In the chemical storage category, Liquid Organic Hydrogen Carriers have shown significant advancements, particularly for mobile and behind-the-meter storage solutions. The primary challenges for this technology are its cost and lower round-trip energy efficiency.

Phase Change Materials (PCMs) are at the forefront of innovation in thermal storage, ideal for coupling with renewable energy sources and localized applications such as rooftop solar installations. The main obstacles here include scalability and efficiency.

The Vanadium Redox Flow Battery emerged the top contender in flow battery-based LDES technologies, with optimal application in front-of-the-meter scenarios. Enhancing round-trip efficiency remains a critical hurdle for wider adoption.

The Overall Winner - Sodium-Ion Batteries.
Sodium-ion batteries are the fastest improving LDES technology, with an improvement rate of 56% in 2024. These batteries are versatile, and applicable both front-of-the-meter, such as near wind or solar farms, and behind-the-meter. They are poised to revolutionize the LDES market by 2028, matching the optimal cost for integrating with renewable energy sources. Their compact footprint and the cost-effectiveness of integrating with renewable sources in the future, position them as the dominant LDES technology for a variety of applications.

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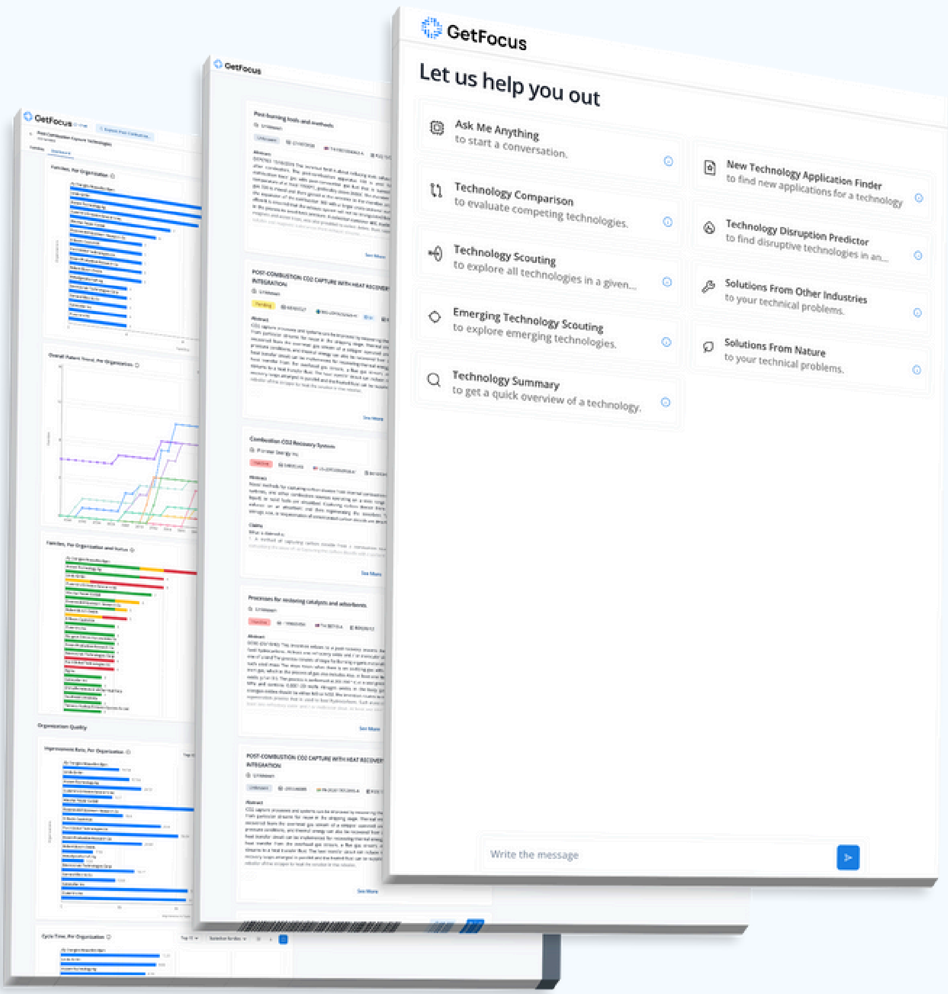
About GetFocus

GetFocus built the world's first platform that can reliably forecast the technological future using advanced AI technologies. It turns out that winning technologies show clear and measurable patterns. We extract these patterns from patent data and make them available in a SaaS tool so businesses can make strategic investments in the right emerging technologies.

Next to forecasting, we enable R&D leaders to get up to speed on new technologies 100X faster by giving them AI-powered tools for trend scouting, technology summaries, and technology deep dives. The entire platform works through natural language and is very easy to use.



Method:

GetFocus orchestrates 3 types of AI to facilitate technology scouting, landscaping, and forecasting.

1

Large Language Models

Used to scout emerging technology areas in any context.

2

Vector search

Used to gather the relevant invention data within each technological area. This dataset is then refined to make sure it accurately represents a technological area.

3

Multivariate regression

Based on invention data and empirically measured technological improvement data is used to forecast technology improvement rates.

Our approach is inspired by research from the Massachusetts Institute of Technology MIT.

Estimating technological improvement speeds is useful because, historically speaking, the fastest improving technology among a set of competing technologies always becomes the dominant solution.

This takes into account the age, industry, application, and "popularity" of the technology and is true for every historical case of technology disruption that has ever been studied.

The improvement speed for each technology is derived from the citation metadata of the inventions associated with each technological landscape.

The Technology Improvement Rate TIR is a compound metric of Cycle Time (how many years does it take for a new generation of a technology to come out) and Knowledge Flow (how large each generational improvement is).

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“In a week with Focus, we achieved more than what we previously could in 9 months."

Trusted by Innovators Globally

About the Authors:

Jard van Ingen,
CEO and co-founder of GetFocus

As CEO and co-founder of GetFocus, the world's first predictive AI analysis platform that accurately and reliably predicts the technological future based on global patent data, Jard van Ingen is responsible for leading and executing the company's vision and strategy, product development at large, and overseeing global sales and strategic partnerships. Energetic and hands-on, Jard is all about making complex tech trends in innovation easy to understand so R&D leaders can navigate the rapidly changing tech world.

Jard holds a master's degree in Intellectual Capital Management and Entrepreneurship from the University of Gothenburg in Sweden and a bachelor's degree in Business and Managerial Economics from the Amsterdam University of Applied Sciences.

Rajvardhan Desai
Research Analyst

With a background in mechanical engineering and IP management, I am working my way to becoming a business generalist while still being connected to my roots in engineering.

At GetFocus, I conduct technical analysis and generate insights about upcoming technologies using the Odin platform. And for fun, I also interpret and theorise what these insights mean for a clients buisness case.Deadlifts and real time criticism of Formula 1 GPs are my weekend rituals, just in case you were interested in knowing what I do beyond playing around with Odin.

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Appendix

1. Table: Representing each LDES technology taken into consideration, their Improvement Rate(%), and Technology Readiness Level (TRL)

Technologies	Classification	Technology Improvement Rate (TIR) 2024	Technology Readiness Level (TRL)
Metal-air Batteries	Electrochemical Storage	21.24%	6
Sodium-sulfur Batteries		21.60%	8
Lithium-ion Batteries		36.70%	9
Sodium-ion Batteries		56.61%	7
Hybrid Flow Batteries	Flow Batteries	22.22%	6
Redox Flow Batteries		24.48%	8
Zinc-Bromine Flow Batteries		34.27%	7
Vanadium Redox Flow Batteries		34.40%	8
Methanol Synthesis Storage	Chemical Storage	15.42%	5
Power-to-Gas (P2G) Storage		19.56%	6
Liquid Hydrogen Storage		19.68%	7
Hydrogen Storage		20.06%	7
Compressed Hydrogen Storage		20.66%	8
Metal Hydrides Storage		21.16%	6
Synthetic Natural Gas (SNG) Storage		21.46%	7
Methanation Storage		22.15%	6
Liquid Organic Hydrogen Carriers (LOHC) Storage		31.15%	5
Ice Thermal Storage	Thermal Storage	13.25%	8
Sensible Heat Thermal Storage		15.32%	8
Thermochemical Storage		15.43%	5
Hot Water Thermal Storage		19.61%	9
Molten Salt Thermal Energy Storage		25.21%	8
Phase Change Materials (PCM) Storage		29.63%	7
Pumped Hydro Storage	Mechanical Storage	13.00%	9
Gravity Energy Storage		13.90%	4
Flywheel Energy Storage		17.50%	8
Compressed Air Energy Storage (CAES)		20.50%	7

What Are TRLs and How Are They Defined?

The Technology Readiness Scale TRL, originally developed by NASA, is widely used across industries to assess the development stage of technologies, especially in fields like aerospace, defense, and energy. The scale ranges from 1 to 9, with each level representing a different stage of technology development.

TRL 1 – Basic Principles Observed: This is the most preliminary stage. It involves the basic observation of scientific principles and the identification of the concept. Theoretical research and scientific study are conducted to support the feasibility of the ideas.

TRL 2 – Technology Concept Formulated: At this stage, the basic technology concepts and applications are formulated. Initial theoretical and experimental proof of concept is developed. This is more about conceptualizing how the technology might work.

TRL 3 – Experimental Proof of Concept: This stage involves active experimentation to validate the theoretical predictions. Laboratory experiments are conducted to physically demonstrate the feasibility of the concepts.

TRL 4 – Technology Validated in Lab: The technology is further developed and validated in a laboratory environment. This includes bench-scale or small-scale testing, typically under simulated or partially simulated environments.

TRL 5 – Technology Validated in Relevant Environment: The technology is demonstrated in an environment that closely represents the real-world application. This stage is crucial for understanding how the technology functions outside of the controlled lab setting.

TRL 6 – Technology Demonstrated in Relevant Environment: A significant step where the technology model or prototype is tested in a relevant environment. This stage demonstrates the technology's performance in scenarios that closely mimic the operational environment.

TRL 7 – Technology Demonstrated in Operational Environment: The prototype is now demonstrated in an operational environment. This is a full-scale, realistic test, showing that the technology works reliably in the intended environment.

TRL 8 – Technology Proven Ready for Production: The technology has been proven to work and is ready for commercial production. It has passed all final tests and validations and is considered mature and reliable.

TRL 9 – Actual Technology Proven Through Successful Operations: The final stage is where the technology is not only proven but also has been actually deployed and used successfully in its final form in real-world operations.