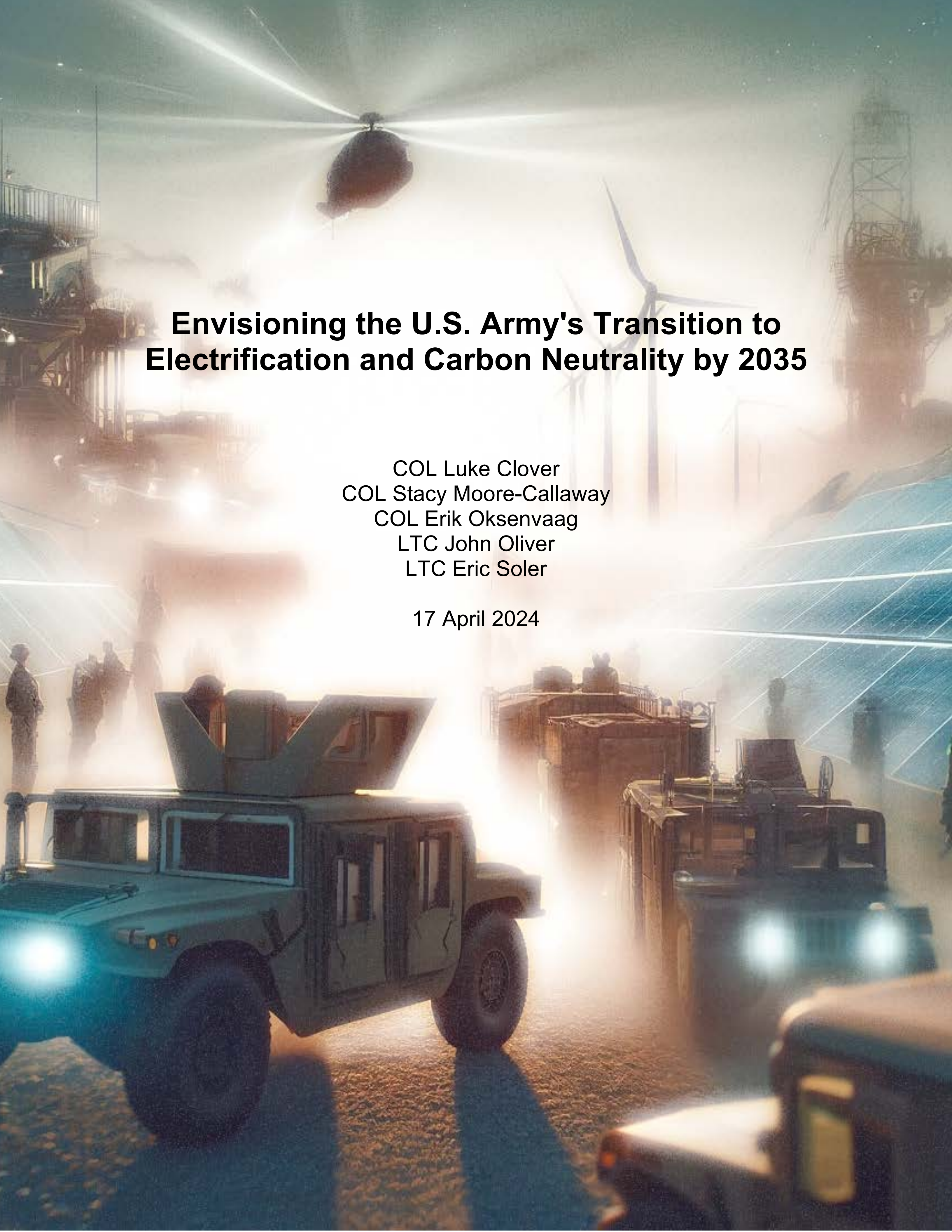


Envisioning the U.S. Army's Transition to Electrification and Carbon Neutrality by 2035

COL Luke Clover
COL Stacy Moore-Callaway
COL Erik Oksenvaag
LTC John Oliver
LTC Eric Soler

17 April 2024

About This Document

The United States Army War College (USAWC) student team, Team Atropos, prepared this document as a group Integrated Research Project, contributing to team members earning a Master of Strategic Studies degree from the USAWC. This product's research, analysis, and production occurred over 28 weeks from October 2023 to April 2024 as part of the in-residence USAWC Senior Service College program. The team consisted of 5 US Army Officers.

The team members were COL Luke Clover, COL Stacy Moore-Callaway, LTC John Oliver, COL Erik Oksenvaag, and LTC Eric Soler. The team conducted their research under the direction of Professor Kathleen Moore, Ph.D., Professor of Data Science, Center for Strategic Landpower and Futures Group, USAWC.

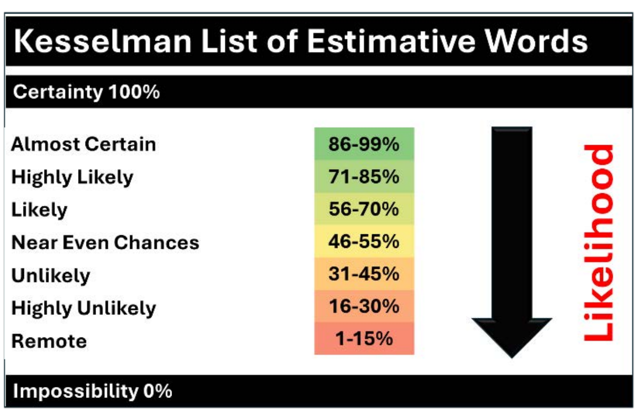
Research Question

What capabilities[1] are likely to become available between now and 2035 to support the transition of the U.S. Army from a carbon-based, energy-reliant organization to an electrified, carbon-free force?

- What viable options are likely to emerge that the Army can invest in to reduce the demand for carbon-based fuels that are now used to power installations and contingency-basing?
- What emerging technologies will likely be available to provide the adequate carbon-free power needed for the tactical vehicles of the future?
- What global infrastructure innovations will be available by 2035 that may impact installation and contingency bases?
- What emerging energy options could preserve and enhance capabilities for the operational Army?
- What obstacles might hinder the implementation of the electrification of the force by 2035?

Terms of Estimative Probability

Team members used the Kesselman List of Estimated Words (Annex B) to define terms of analytic probability. Using this scale, team members provided an estimate for each analytical report in this document to forecast the probability that a particular claim would occur.



Kesselman List of Estimative Words	
Certainty 100%	
Almost Certain	86-99%
Highly Likely	71-85%
Likely	56-70%
Near Even Chances	46-55%
Unlikely	31-45%
Highly Unlikely	16-30%
Remote	1-15%
Impossibility 0%	

**Note, Kesselman utilizes "Chances a Little Better [or Less]"; team replaced this with Near Even Chances for readability*

[1] Capabilities refers to both products and processes.

Source Reliability

Team members noted each source with a hyperlink that described its reliability as Low ([L]), Moderate ([M]), or High ([H]). They determined source reliability using the Standard Primary Source Trust Scale (Annex C).

Analytic Confidence

The overall analytic confidence of this estimate is moderate. The questions asked were complex, and the timeline was relatively short due to the competing academic requirements of the USAWC core curriculum. Source reliability and corroboration were predominantly moderate to high. However, the analysts are not subject matter experts and worked individually and collaboratively to research and answer the questions. Theoretical predictions varied, and research sometimes conflicted, specifically with time-based predictions on technical reliability or wide-scale adoption. Lastly, given the lengthy time frame of the estimate, this report is sensitive to change due to new information.

Report Organization

This report is available in PDF and hard copy formats, with the PDF version including links to the source materials. The main body contains five sections: Redundant Power Generation, Assured Power, Smart Tech Synergy, Obstacles, and Other Findings. On April 17, 2024, Team Atropos briefed Hon. Jacobson on the key findings (Annex H).

Table of Contents

Key Findings

It is highly likely (71-85%) that a convergence of emerging capabilities will occur between now and 2035 to support the transition of the US Army from a carbon-based, energy-reliant organization to an electrified, carbon-free force. Despite challenges with supply chains, infrastructure, and the workforce, 11 interconnected developments in three emergent capability domains: redundant power generation, assured energy, and smart tech synergy integration support the transition to a decarbonized force. All technologies are either currently available or will be by 2035.

Table 1: Emergent Capability Domains

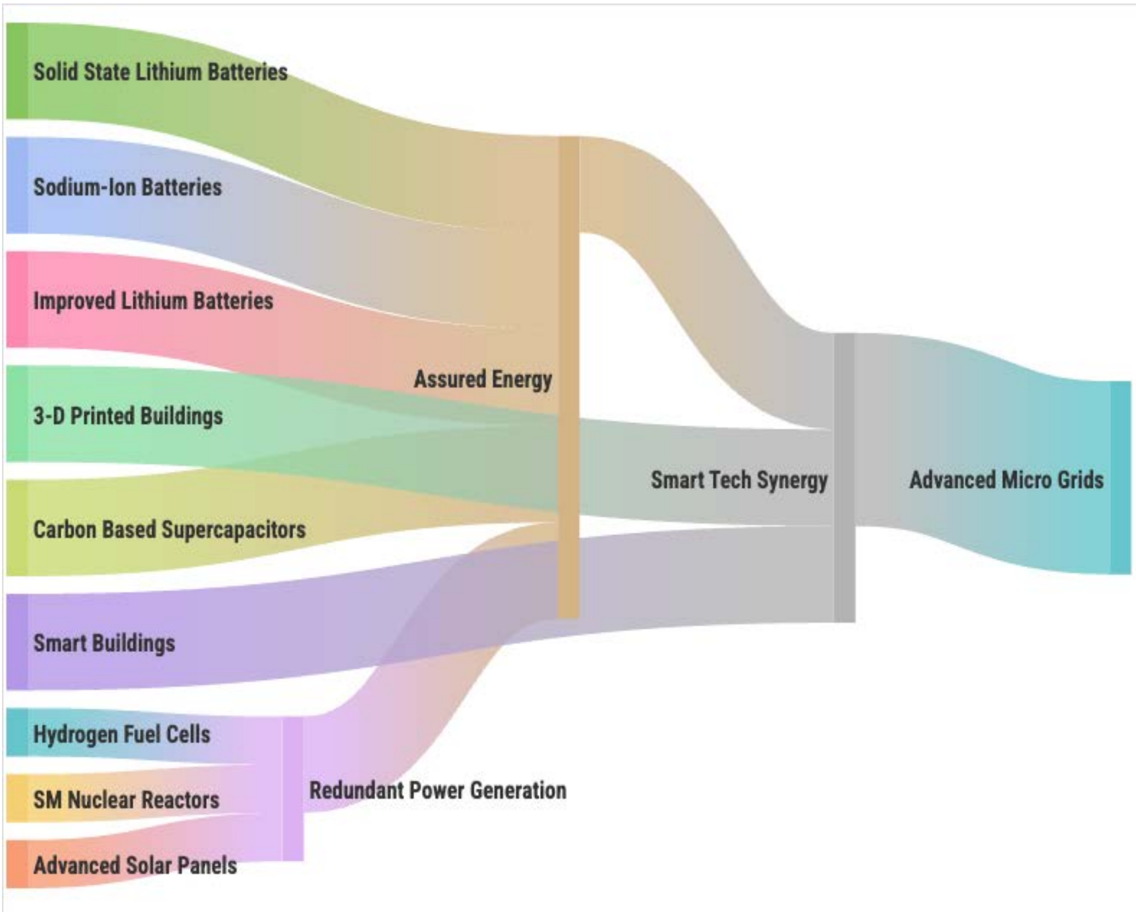
Emergent Capability Domains		
Redundant Power Generation	**Assured Energy**	**Smart Tech Synergy**
Small Modular Nuclear Reactors	Solid State Lithium Batteries	3D Printed Buildings
Advanced Bi-Facial Solar Panels	Hybridized Medium Size Vehicles	Smart Buildings
Large Vehicle Hydrogen Fuel Cells	Sodium-Ion Batteries	Advanced Microgrids
	Cement Supercapacitors	
	Improved Lithium-Ion Batteries	

These 11 capabilities are not just standalone advancements but are highly interdependent and will likely (56-70%) amplify each other's effects, as depicted below. This interconnectedness drives the need for a comprehensive and robust transition plan. An eigenvector analysis reveals that advanced microgrids hold a central position in the network of technological advancements, acting as a critical hub that not only reaps the benefits from developments in related fields, such as battery technology, but also amplifies the efficacy of other technologies through synergistic applications.

The interdependent technologies are grouped by function or impact into emergent capability domains. Redundant Power Generation consist of those technologies related to power generation. Assured Power consists of capabilities that store or regulate power. Smart Tech Synergy holds the capabilities that enable the efficient use of all other technologies.

When examining technologies in the order of their development, we find that three capability domains seem to create the greatest impact when they are progressively implemented. First, Redundant Power Generation develops; these then feed into Assured Energy, and finally, both contribute to the development of Smart Tech Synergy. Understanding how these domains interact and the timeline for technology development allows leaders to prioritize investments in new technologies.

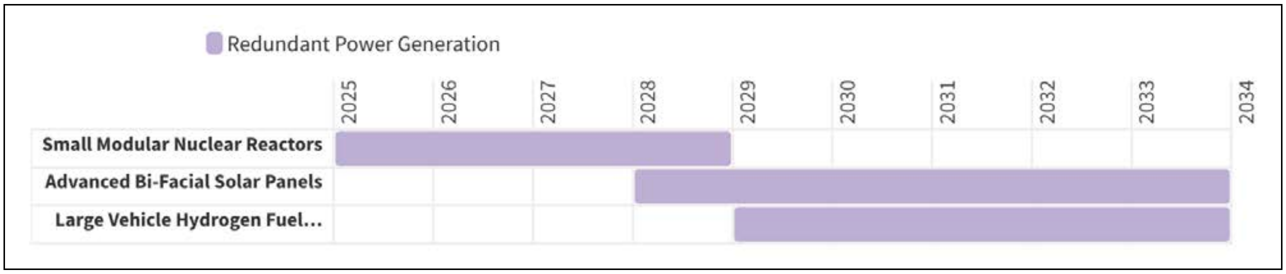
Chart 1: Progressive Implementation of Emerging Technologies



Key Findings 1: Redundant Power Generation

Distributed power generation, along with varied power generation capabilities, is likely (56-70%) to enable green technology transitions by 2029 due to power generation modularity, increased power generation efficiency, and increased operating reserves. By leveraging local sources to meet specific needs, communities can select their preferred energy type, optimizing green power generation and increasing resilience.

Chart 2: Redundant Power Generation Commercial Availability Timelines



Small Modular Nuclear Reactors

By 2030, it is highly likely (71-85%) that the Department of Defense will have nuclear microreactors due to simultaneous prototype projects, an increase in research funding, and commercial applicability. Utilizing this capability could curb some of the Army's 56 million metric tons of Carbon Dioxide (CO_2) emissions each year. Despite fuel availability issues, regulatory hurdles, and waste concerns, microreactors' flexibility and economic efficiencies will drive rapid development.

The rapid advancement of prototypes in the small nuclear energy sector underscores the increasing viability of microreactor technology. Numerous companies are collaborating with research institutions, such as the Idaho National Laboratories, to streamline commercialization efforts by the decade's end. The significant investments by multiple countries, including federal subsidies totaling over USD 1 billion by the US and USD 600 million by the UK, underscore a global commitment to microreactor development.

These reactors offer the advantage of being deployable anywhere globally, with initial cost estimates comparable to the US power grid. The potential to replace diesel generators in remote or closed grid locations further enhances their market viability. Additionally, the expanding market for microreactors in various sectors, including distributed energy and disaster relief, augurs well for their commercial success.

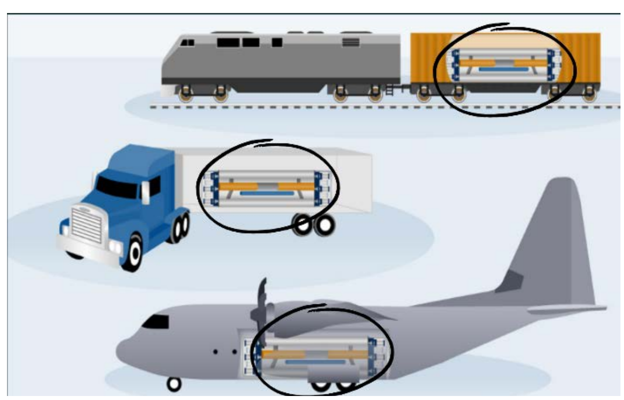


Figure 1- Microreactors shown in possible portable configurations

Advanced Bi-Facial Solar Panels

The development and deployment of solar-powered rapid battery charging systems is likely (56-60%) to occur by 2030. This forecast is supported by recent technological breakthroughs in solar panel efficiency, specifically the emergence of tandem perovskite solar cells and bifacial solar panels, as well as advancements in flexible solar-capturing materials. While challenges persist in large-scale production for military applications, ongoing advancements in manufacturing techniques are expected to overcome these obstacles within the next five years.

Current silicon cell solar panels have reached a maximum efficiency capacity of 20 to 22 percent. However, the emerging technology of tandem perovskite solar cells can potentially increase solar panel efficiency to 45 percent. Despite facing durability and production challenges due to unique crystal structures, recent investments by the Department of Energy aim to enhance the durability and commercialization of perovskite cells, facilitating their widespread adoption.


Figure 2- Flexible Bi-Facial Solar Panels

Bifacial solar panels, which capture sunlight from both sides, offer additional energy capture by utilizing direct and reflected sunlight. Coupled with tandem perovskite technology, bifacial panels demonstrate a potential energy gain of up to 45 percent over static panels. Flexible perovskite solar cells provide durability and deployment options, maintaining efficiency even after repeated bending cycles. The marketability of flexible panels, particularly in miniature consumer electronics, suggests increasing research, development, and production capacity.

Large Vehicle Hydrogen Fuel Cells

Efficient hydrogen fuel cells are highly likely (71-85%) to be widely available by 2030, offering clean and sustainable energy for large vehicles and small buildings. These fuel cells convert hydrogen's chemical energy into electricity through an electrochemical reaction, with only heat and water as byproducts. Despite challenges like high production costs, limited infrastructure,

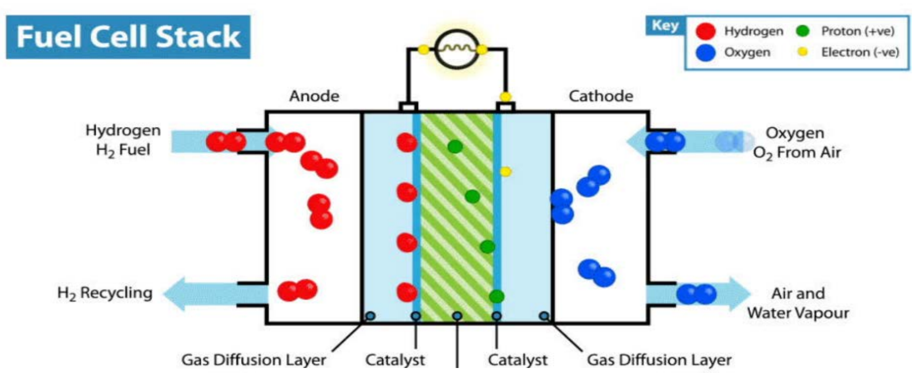


Figure 3- Hydrogen Fuel Cell Function

and storage constraints, fuel cells present a promising solution to decarbonize transportation and power generation sectors.

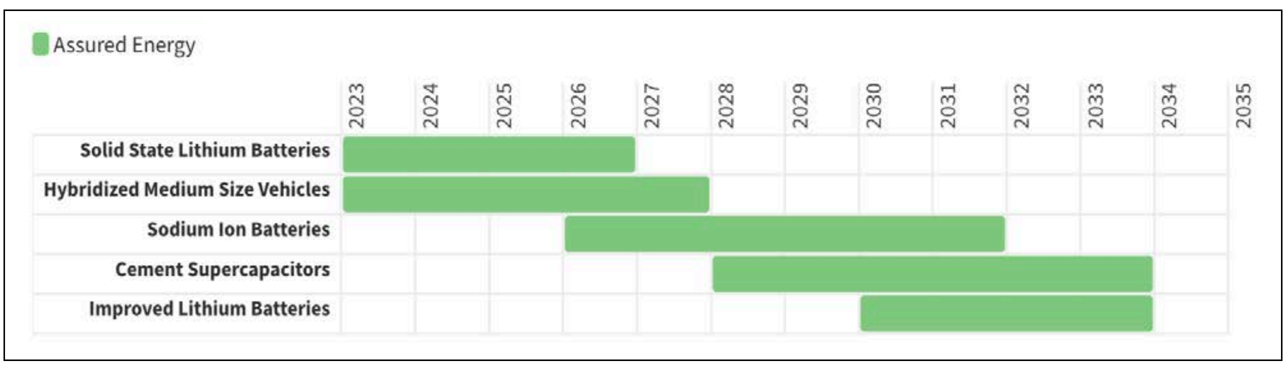
Fuel cells boast advantages such as rapid refueling, high energy density, and versatility, making them suitable for various applications, including heavy-duty transportation and shipping. Major vehicle manufacturers like Hyundai, Daimler, and Volvo are investing in hydrogen-powered fuel cells, recognizing their potential for longer-range and faster refueling than batteries. Moreover, fuel cells offer scalability and flexibility, with potential applications in ships, aircraft, and mobile generators.

Infrastructure remains a significant hurdle to widespread adoption, with limited retail hydrogen stations and challenges in clean hydrogen production and storage. Despite these obstacles, targeted investment and government incentives, such as tax credits, aim to accelerate the development and deployment of fuel cell technology, positioning it as a leading green energy solution for large vehicles and industrial applications.

Key Findings 2: Assured Energy

It is almost certain (86-99%) that advances in energy storage and delivery will provide increased reliability to commercial and military power supplies. Wind and solar energy produce excess energy at certain times of the day, fall short of demand during others, and are also highly seasonal. It is imperative to capture excess energy and return it quickly to the grid during times of increased demand. Innovations in energy storage technologies, including solid-state lithium batteries, medium vehicle hybridization, sodium-ion batteries, cement supercapacitors, and improved lithium batteries, offer efficient energy delivery across a broad array of applications.

Chart 3: Assured Energy Commercial Availability Timelines



Solid State Lithium Batteries

Solid-state Lithium-Ion (LI) Batteries are highly likely (71-85%) to reach wide commercial use by 2030. Solid-state batteries use solid electrodes and a solid electrolyte to create higher energy density, lower risk of fire, and potentially higher mileage for EVs. These improvements enhance the performance of EVs and industrial energy storage, making them attractive solutions for automakers and green energy providers.

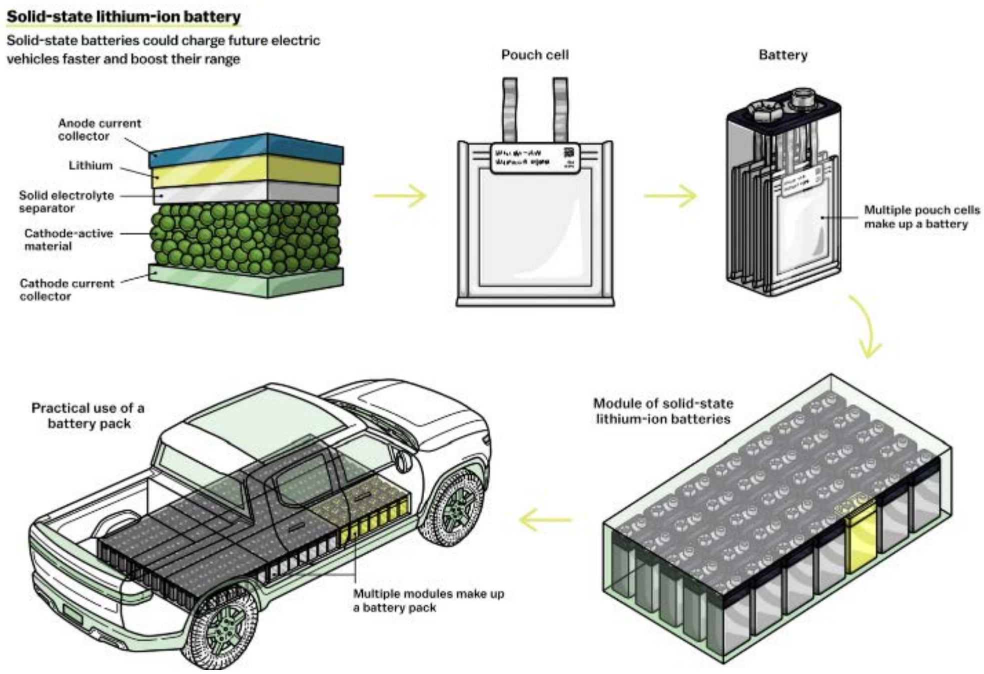


Figure 4- Solid-State Lithium-Ion Battery Composition

By utilizing solid electrodes and electrolytes, solid-state lithium-ion batteries offer higher energy density compared to traditional lithium-ion batteries that use liquid electrolytes. This increased energy density allows for more electrical energy storage within the same battery volume, enabling longer driving ranges for EVs and improved performance in various energy storage applications.

Despite their manufacturing complexity, mechanical fragility, and high cost compared to traditional LI batteries, solid-state batteries' higher energy density, reduced fire risk, and potential for increased mileage make them an attractive option for green energy producers and EV manufacturers.

Hybridized Medium Sized Vehicles

The significant advantages of hybridized vehicles make it highly likely (71-85%) that the Army will enact this technology in medium tactical vehicles by 2035. The electrification of heavy-wheeled vehicles presents the US Army with promising tactical and logistical advantages for future battlefields, encompassing reduced noise signatures, simplified drivetrains, and a reduction of petroleum-based fuels. Additionally, these vehicles can store and distribute power across the battlefield as part of a tactical microgrid.

Figure 5- Onboard Power Supply for Hybridized Vehicle

Sodium-Ion Batteries

It is nearly certain (86-99%) that sodium-ion batteries will replace lithium-ion batteries in vehicle applications. Sodium-ion batteries represent a promising alternative to lithium-ion batteries, driven by the need to address supply chain vulnerabilities and environmental impacts of lithium-ion technology. By utilizing more abundant and less environmentally impactful materials, sodium-ion batteries offer a potential solution to mitigate the reliance on rare earth metals such as lithium, cobalt, and nickel.

One of the critical advantages of sodium-ion batteries is their utilization of sodium and manganese as primary elements, which are more readily available and less prone to geopolitical tensions compared to lithium and cobalt. Sodium is abundantly available on land and in seawater, providing a sustainable and cost-effective raw material for battery production. This helps to reduce dependency on scarce resources and alleviate concerns related to supply chain disruptions.

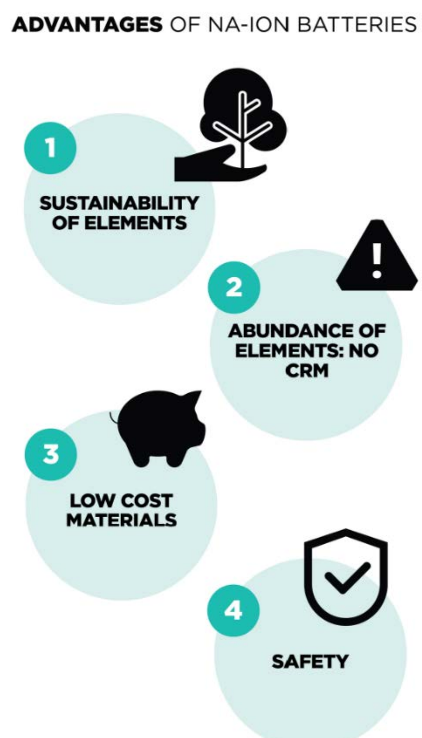


Figure 6- Advantages of Sodium-Ion Batteries

Moreover, sodium-ion batteries offer comparable storage capacity and energy density to lithium-ion batteries. Research and development efforts focused on optimizing electrode materials and electrolyte formulations to enhance the performance of sodium-ion batteries, with promising results in terms of cycle life and safety. Despite not yet meeting the performance standards set by lithium-ion batteries, sodium-ion technology is rapidly advancing, driven by its potential cost savings and compatibility with existing battery manufacturing infrastructure.

Cement Supercapacitors

It is highly likely (71-85%) that cement supercapacitors (SCs) will play a critical role in energy storage by 2030, driven by their versatility in regulating energy from renewable sources like wind and solar power. Cement SCs offer significant advantages over traditional batteries, including greater storage capacity, operational flexibility in extreme temperatures, and a superior number of charge/discharge cycles. Despite their lower energy density compared to batteries, cement SCs excel in providing storing large quantities of energy and releasing it quickly for use in a power grid.

Cement SCs are made by mixing carbon black and cement, allowing the foundation of a house to store the equivalent of one day's electricity supply. Cement supercapacitors are also ideal for use in green energy production facilities. These supercapacitors integrate into the foundation of wind turbines and solar panel arrays, reducing the need for additional space for energy storage. Additionally, cement SCs have hundreds of thousands of charge/discharge cycles and operate at extreme temperatures, ensuring they can store energy in austere climates where many green energy platforms are located. Cement supercapacitors do not rely on rare earth metals or polluting materials in their production, making them less expensive and reducing their environmental impact.

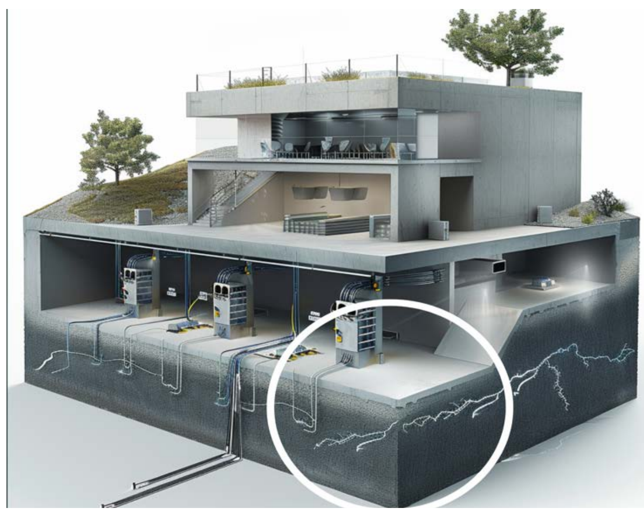


Figure 7- Cement Supercapacitor powering a building

They do, however, require large quantities of sand to make cement. The scarcity of sand as a significant cement component is a global concern due to rapid urbanization, infrastructure development, unsustainable extraction practices, and limited suitable sources. This scarcity leads to environmental degradation, rising costs, and disruptions in the global supply chain, prompting the exploration of alternative materials and technologies to mitigate the shortage.

Improved Lithium-Ion Batteries

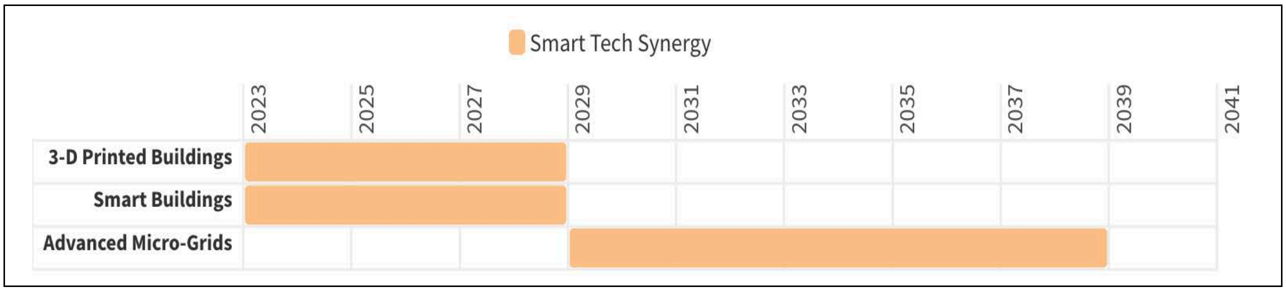
It is almost certain (86-99%) that improved lithium-ion batteries will be available by 2030. Industry is motivated by potential cost savings, reduced supply chain risks, and minimized environmental footprints associated with new battery technologies. The next generation of LI batteries incorporates advanced materials to enhance key aspects such as energy density, charging speed, lifespan, and safety. For instance, the integration of silicon anodes and the substitution of sulfur for cobalt are notable advancements aimed at achieving commercialization by 2031. Significant corporate investments in research and development support these innovations.

The drive for improved LI batteries is motivated by their potential benefits, including cost savings, reduced supply chain risks, and environmental sustainability. Despite challenges in achieving large-scale manufacturing and optimizing overall performance, the progress made in advanced materials and battery technologies paves the way for significant improvements in LI battery performance by 2030.

Key Findings 3: Smart Tech Synergy

It is almost certain (86-99%) that data analytics and the Internet of Things (IoT) will improve energy efficiency and reduce the carbon footprint of installations and contingency bases. 3-D-printed buildings, smart buildings, improved industrial battery storage, liquid-cooled data storage, and smart data analytics enhance energy systems' efficiency, reliability, and adaptability to evolving needs and conditions.

Chart 4: Smart Tech Synergy Commercial Availability Timelines



3D Printed Buildings

The utilization of 3D printed buildings is likely (56-70%) to have significant construction potential for installations or expeditionary bases by 2035. This is attributed to the advantages of reduced construction time, lower labor costs, decreased resource consumption, and waste generation. Despite challenges such as high initial costs, on-site placement complexities, and the absence of standardization in the US construction sector, 3D construction printing emerges as a sustainable and cost-effective option for future infrastructure projects.

3D construction printers demonstrate efficiency and speed, reducing construction durations compared to traditional methods. For instance, China's construction of a five-story 3D-printed apartment building within 45 days showcases the technology's potential for rapid construction. As technological advancements progress, construction times and labor requirements should decrease further, making 3D printing a viable solution for the swift development of military installations or forward basing by the US Army.

Despite its potential benefits, 3D construction printing faces challenges, including high operational costs and difficulties in site placement due to the large size of printers. Additionally, regulatory practices and construction codes in the architectural field require updates to accommodate this emerging technology effectively.

While 3D construction printing offers promising solutions to enhance construction efficiency and sustainability, overcoming existing challenges and fostering regulatory support are essential for widespread adoption across the construction industry.

Smart Buildings

Smart buildings are likely (56-70%) to revolutionize installation construction by 2040, offering significant benefits such as improved energy efficiency, enhanced sustainability, and cost reduction. By leveraging advanced automation and intelligent systems, smart buildings can optimize energy consumption in real-time, thereby reducing waste and minimizing environmental footprint. Despite their potential, high implementation costs, lack of standardization, and data security concerns may hinder their adoption in military construction.

Current buildings often suffer from energy waste and inefficient systems, contributing to unnecessary expenses and increased environmental impact. Smart buildings address these challenges by employing automation and intelligent algorithms to analyze energy patterns and identify optimizations, resulting in up to 30 percent savings in energy consumption.

From a financial standpoint, smart buildings offer substantial cost savings by identifying energy waste and reducing utility expenses. Real-time tracking and data analysis enable predictive maintenance and power redistribution, significantly reducing operating expenses. Despite the perception of high initial costs, the long-term savings justify the investment, with potential reductions of up to 20 percent in utility costs.

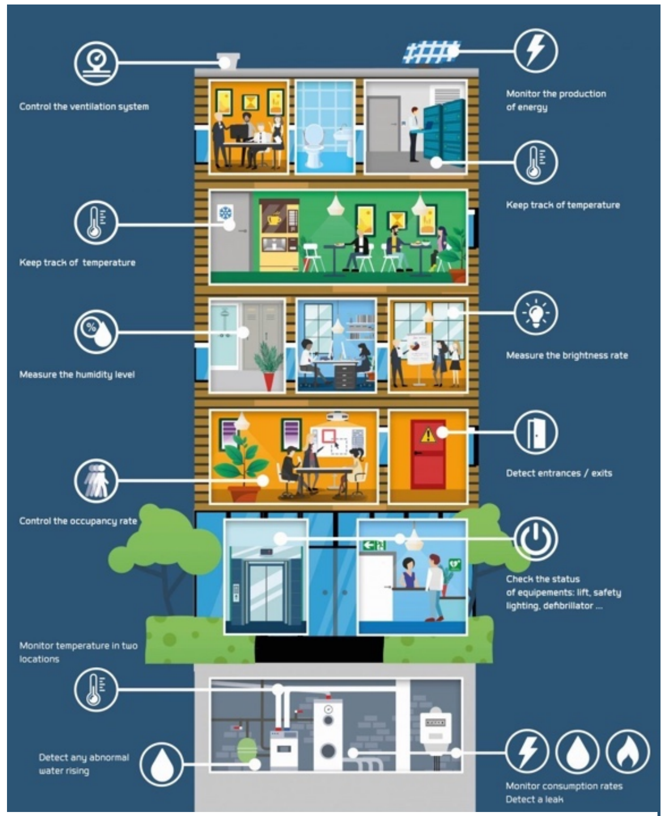


Figure 8- Components of a Smart Building (for a larger image, see Annex H)

However, several challenges may impede the military's adoption of smart building technology, including high implementation costs, lack of standardization, and data security concerns. Retrofitting current structures with management solutions can be costly and time-consuming, but pilot projects can test feasibility and assess benefits. Moreover, focusing on interoperability and developing open architecture can ensure seamless integration of various systems while mitigating data security risks.

Advanced Micro Grids

Advanced microgrids enabled by data analytics and new battery storage technologies are highly likely (71-85%) to play a critical role in achieving installation energy stability and resilience by

2035, offering solutions to manage grid optimization, enhance grid stability, and improve demand response efficiency.

Data analytics leverages AI and machine learning techniques to optimize microgrid operations, reduce downtime, and allocate resources efficiently. Real-time monitoring enables prompt responses to anomalies, enhancing grid stability and reliability.

Moreover, data analytics aids in predictive maintenance, identifying potential equipment failures, and ensuring consistent power supply. This approach significantly reduces maintenance costs and extends equipment lifespan, as evidenced by successes like TEPCO's grid maintenance in Japan. Data analytics also improves demand response efficiency, resulting in substantial energy savings, cost reductions, and reduced greenhouse emissions.

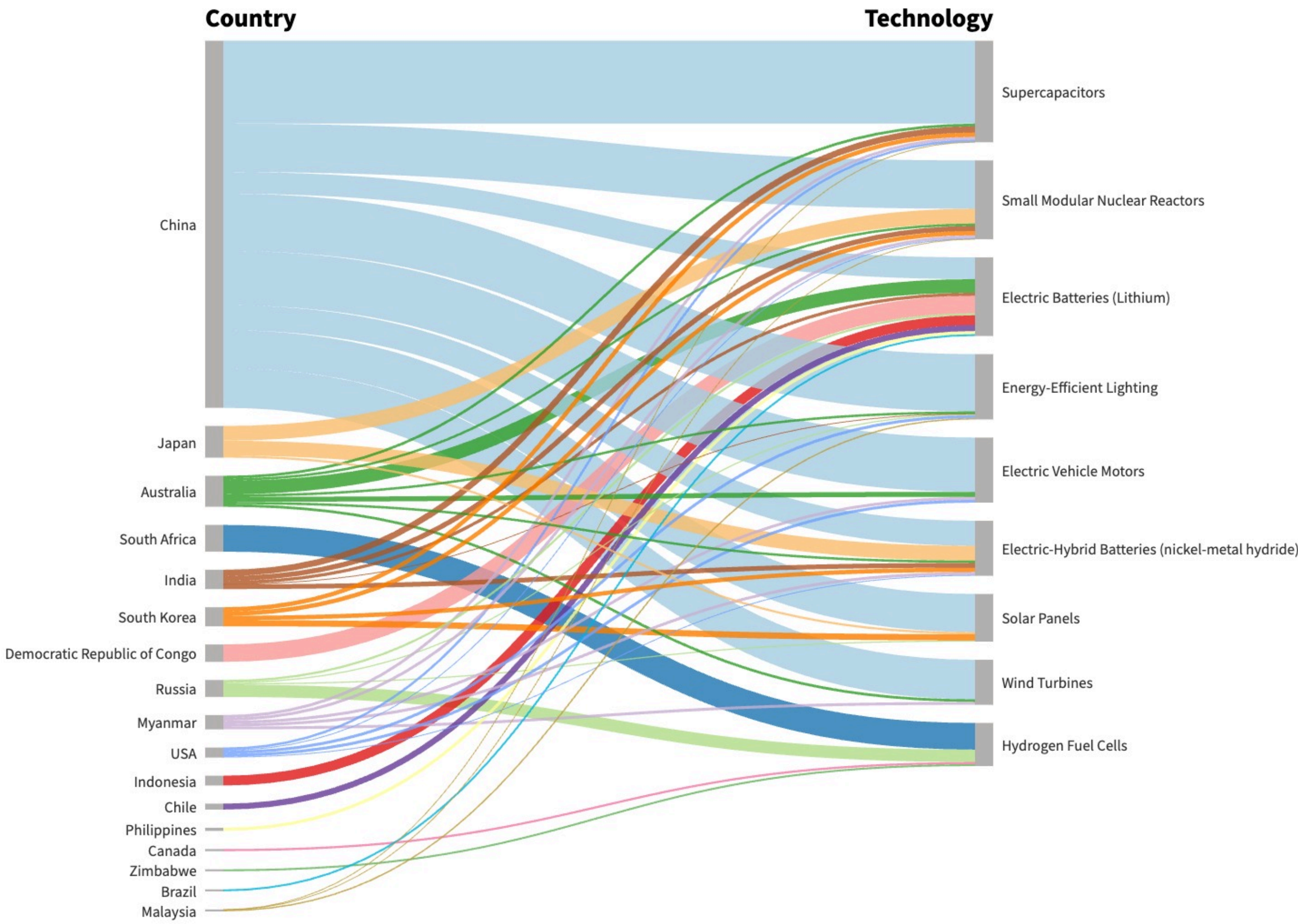
However, challenges such as data volume and network interoperability persist. Standardization of grid components, investment in communication technologies, and workforce education are crucial for addressing these challenges and ensuring a future of reliable energy stability.

Key Findings 4: Obstacles

Numerous obstacles exist to decarbonization, including challenges with supply chains for rare earth metals, infrastructure upgrades and policy, workforce development, and managing the transition's costs. The wide range of influences on a successful green transition makes it impossible to control all the variables impacting implementation. Despite these impediments, careful conditions setting can mitigate some of the impacts of decarbonization.

The production of almost every mentioned capability heavily relies on rare earth elements, especially for battery technologies and solar panels. These elements are in high demand due to worldwide efforts to reduce carbon emissions. However, a major issue arises as a considerable portion of the rare earth element supply is situated in countries that are either adversaries of the United States or have questionable labor practices. Despite significant investment in mining and the global push for decarbonization, the limited availability of rare earth elements, their specific geographical locations, and the challenges associated with extracting these minerals will impose constraints on their accessibility. Hydrogen fuel cells, sodium-ion batteries, cement supercapacitors, and 3D-printed buildings are all capabilities that have a lower environmental impact than those using rare earth metals supplied via problematic supply chains. These are also some of the most transformative technologies found in Team Atropos' research. Additionally, there are viable supplies of lithium from Australia and major investment in domestic battery production by the Biden administration that will allow Lithium-ion batteries to support the green energy transition for the foreseeable future.

Chart 5: Exports of Rare Earth Elements by Country to Green Technologies



Significant challenges exist regarding the infrastructure necessary for the green energy transition. The power transmission architecture in the US is fractious, with few poorly regulated connections among major power grids across the country. Each color on this map illustrates a separate regional or local power grid. This lack of connection hinders the ability to balance energy across the country, making it nearly impossible to provide excess electricity generated in one part of the country that is available to high-demand areas in other parts of the country.

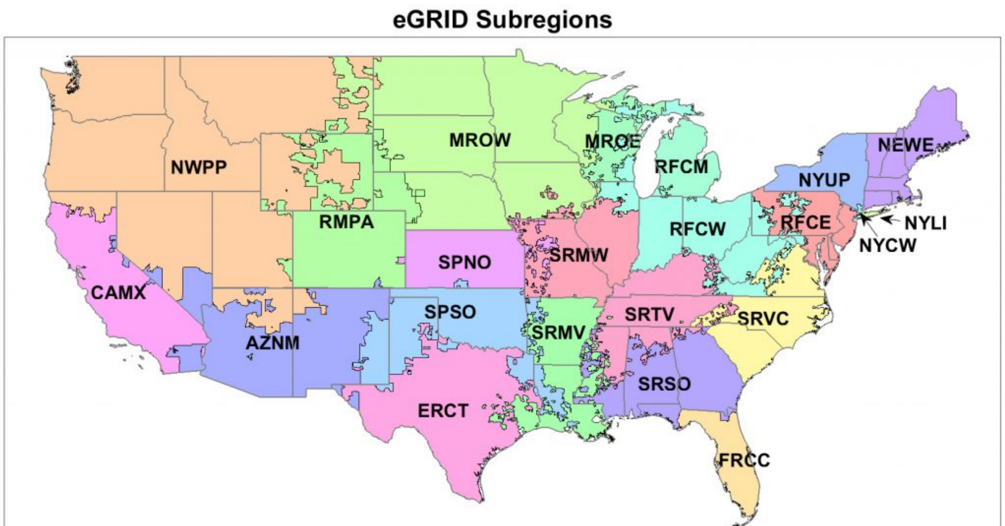


Figure 9- U.S. Grid System by provider

Additionally, the cost of linking the grid systems via high-power transmission lines is prohibitive. For the past two decades, electricity consumption in the US has remained stable, creating an environment where private electricity producers have little economic motivation to construct additional infrastructure. This is why localized redundant power generation is an integral part of decarbonization.

There are also issues with the charging and refueling infrastructure for electric and hydrogen-fueled vehicles. While there are many EV charging stations around the United States, they are not as prolific as gas stations and are not uniformly distributed around the United States. While hydrogen fuel cells are a promising technology, there are only fueling stations in California and Hawaii, meaning that refuel stations would have to be built in order for fuel cells to be widely accepted.

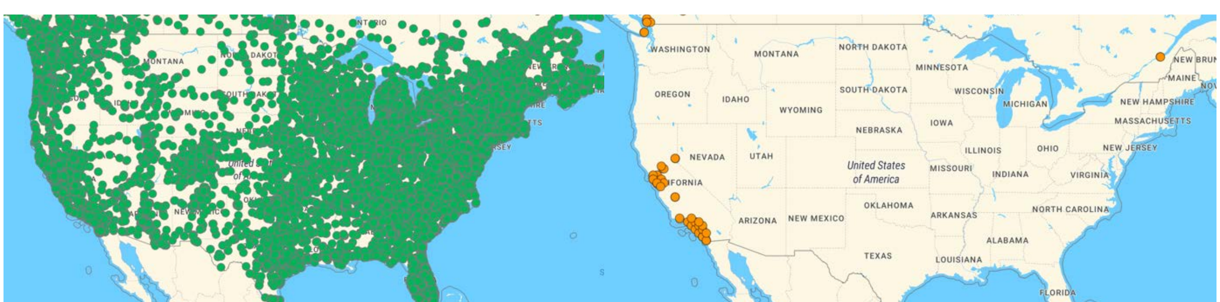


Figure 10- Electric Charging Stations (Green) vs Hydrogen (Orange) Charging Stations

Changing technologies have implications for both the civilian and military workforce. With the successful transition to green energy sources, more technicians, data analysts, engineers, and specialized mechanics are needed. Human Resource Command must develop military occupational specialties to operate and maintain tactical microgrids and repair electric and hybrid equipment. The ability to simultaneously train new skills and teach the skills required for traditional equipment is uncertain. Adopting new technologies may impede the workforce's capacity to keep up with the workload generated.

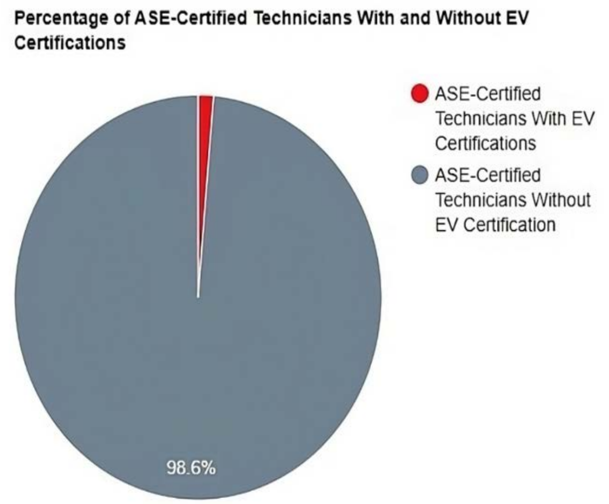
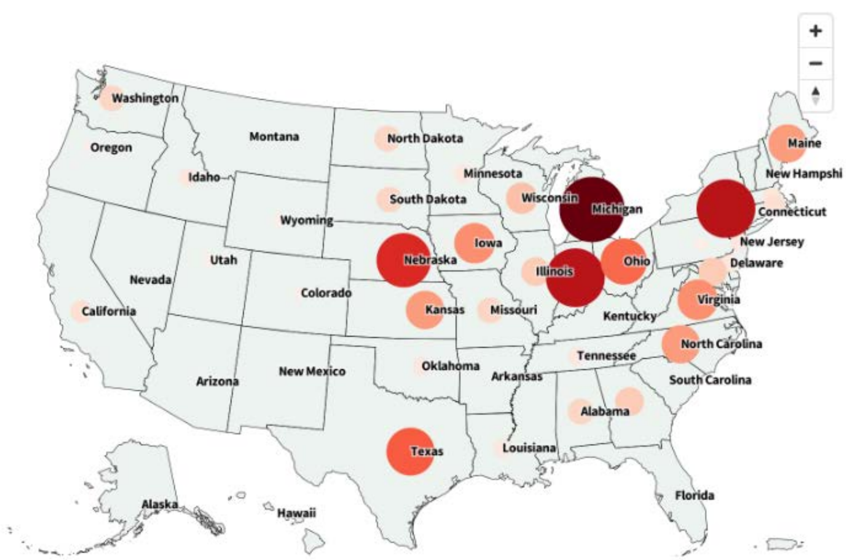


Figure 11- ASE Certified Technicians with EV Certifications

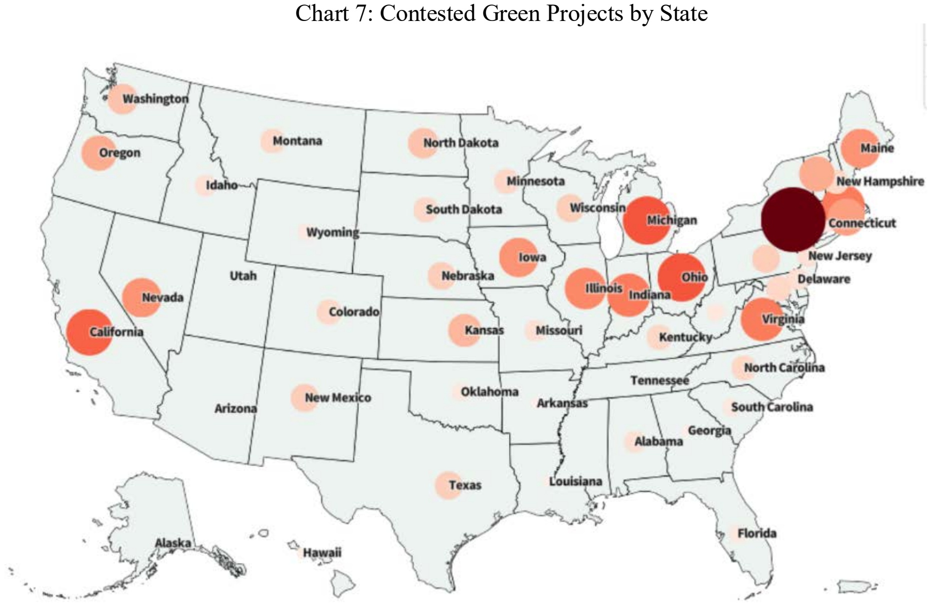
Chart 6: State and Local Restrictions on Green Projects



There are also challenges with restrictive state and local policies on zoning for and installation of capabilities like wind and solar farms that will increase the time horizon and costs for green energy projects. On this chart, we demonstrate the total number of state and local laws restricting the location, type, or size of green energy projects in each state. There are several states, like Utah, that have few state and local restrictions but that also have relatively few green energy projects to restrict due to other economic factors.

State and local laws are not the only difficulty facing green energy projects. This chart shows the number of contested projects by state. This shows that even when there are few laws restricting projects, local organizations may still work against the construction of such projects. Every delay raises the cost of construction. California is a good example of this phenomenon. There are clearly places where the regulatory environment is better for green energy projects than others.

Chart 7: Contested Green Projects by State



Decarbonization entails substantial transition costs. In addition to the power infrastructure challenges mentioned above, maintenance facilities must be upgraded to accommodate hybrid and electric vehicles' heightened lifting capacity and power requirements. Vehicle chargers must be installed, and other accommodations must be made to buildings and control centers to use new capabilities effectively. There are also costs associated with holding repair parts for legacy and modernized fleets and the costs of dual workforces to maintain both fleets.

Section 1: Redundant Power Supply

Stable Nuclear Microreactors Highly Likely by 2030

Executive Summary

By 2030, it is highly likely (71-85%) that the Department of Defense will have nuclear microreactors due to simultaneous prototype projects, an increase in research funding, and commercial applicability. Utilizing this capability could curb some of the Army's 56 million metric tons of Carbon Dioxide (CO_2) emissions each year.[H] Despite fuel availability issues, regulatory hurdles, and waste concerns, microreactors' flexibility and economic efficiencies will drive rapid development.

Discussion

Research shows that diverse scientists at various institutions drive major breakthroughs, supported by public and private investment[M]. Numerous companies are creating prototypes and conducting experimentation through the Idaho National laboratories between now and 2026 to reach commercialization by the end of the decade.[H] This increases the likelihood of product success. These prototypes seek to reduce the size of the reactors, increase stability, lower manufacturing costs, and ease regulatory constraints, all of which are critical components of viability. In addition to the U.S., 15 other countries are investing in the field.[H] The high level of scientific advancement, prototype development, and the numerous organizations conducting parallel research make it highly likely that microreactors will be commercially available by 2030. Shifting to nuclear energy production would reduce CO_2 emissions and create energy independence,

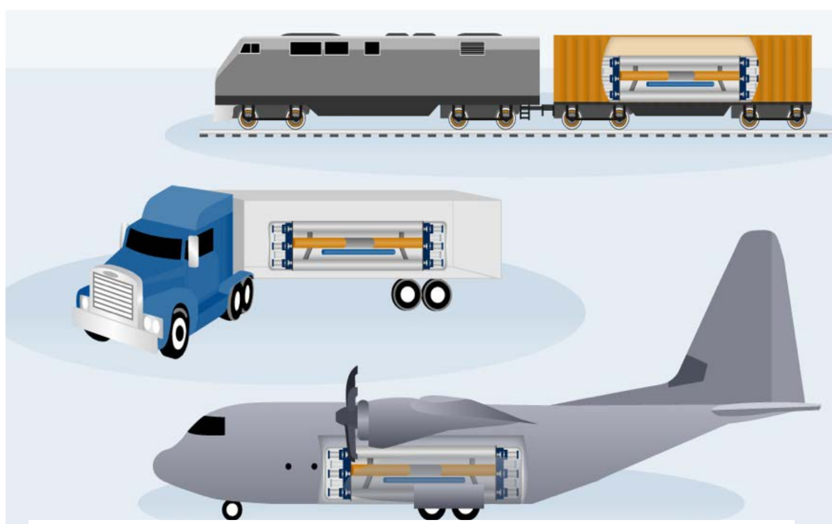


Figure 2- Microreactors shown in possible portable configurations[H]

Federally subsidized funding for advanced technology development significantly increases long-term market options for heavy research and development products.[M] Multiple countries are providing government subsidies to finance microreactors, including over USD 1 billion by the U.S. and over 600 million by the United Kingdom.[H] The FY24 Department of Energy budget allocates over 130 million to advanced reactor development.[H] This funding is a subset of the 1 billion the department allocates towards nuclear energy, which is over 33 percent of its budget and more than other renewable energy sources. The current private market valuation of companies developing atomic energy is 3.5 billion, with NASDAQ projecting estimates of 8 billion by 2030.[M] These valuations increase the likelihood of sustained investment. Investments in nuclear energy and market stability demonstrate a significant commitment to the technology.

Currently, solar power remains the cheapest source of renewable green energy. However, this power generation method lacks economies of scale due to size constraints and seasonal limitations.[M] However, designers intend small microreactors to serve globally anytime, anywhere, with an initial cost estimate placing their kWh at levels comparable to the U.S. power grid.[M] However, the actual value lies in the ability to replace diesel generators at remote and closed grid locations, with initial estimates showing microreactors as cost-competitive alternatives to fossil fuel-burning generators.[M] A green energy alternative with no economic barriers to entry increases the likelihood of commercial success. Additionally, the market for these products increases as they become more viable, with markets opening in "isolated operations, distributed energy, resilient urban, disaster relief, and marine propulsion."[M]

Micronuclear reactors are hindered by the scarcity of specialized nuclear fuel, varying international atomic energy regulations, and the challenge of waste management. The nuclear materials required are highly refined and not yet available in the civilian sector. Additionally, global regulations on atomic energy differ, creating obstacles to commercialization. Lastly, this type of power generation creates waste that the current civilian market needs help processing. To solve these issues, federal governments must assist in establishing fuel and waste management markets by signing long-term purchasing and disposal contracts with companies.[M] This creates a bridge market that supports access to both services until the small modular reactors prove to be economically sound and the market fills the gap.

Analytical Confidence

The analytic confidence for this estimate is *moderate.* Sources were generally reliable and tended to corroborate each other. There was adequate time, but the analyst worked alone and did not use a structured method. Given the extended timeline for this estimate, this report is sensitive to change due to new information. Specifically, this report is sensitive to any increased capital costs for commercial viability as market drivers influence development timelines.

Author: LTC John M. Oliver

Solar Powered Rapid Charging of Batteries Likely by 2029

Executive Summary

The development of solar-powered rapid charging of batteries will likely (56-70%) occur by 2029 due to advances in efficiency, bi-facial panels, and flexible capturing material. Despite the incremental advances in solar panels over the past 20 years, recent technology breakthroughs will likely create deployable solar power by creating efficient panels that maximize energy capture in an easily deployable configuration. Large-scale production for military requirements may prove challenging in the next five years, but manufacturing techniques will likely overcome production issues.

Discussion

Traditional silicon tiles, like the ones on roofs, can convert about 20 to 22 percent of the sunlight they catch into electricity. [M] Silicon technology limits any increased efficiency. A new type of panel called tandem perovskite cells can double that efficiency by up to 45 percent. [H] This means the same amount of sunlight produces more electricity. The new perovskite arrays have been tested and shown to reach 33.7 percent efficiency, with breakthroughs occurring quickly. Their efficiency has increased fast, especially in the last two years. [H] These perovskite cells are not without issues; they are fragile, and current technology limits durability. Perovskite cells face durability and production challenges due to unique crystal structures. However, in 2023, the Department of Energy invested USD 8.3 million to increase the durability and commercialization of perovskite cells.[M] The overarching benefit is that higher efficiency in plates means they can charge devices more quickly and require fewer systems.

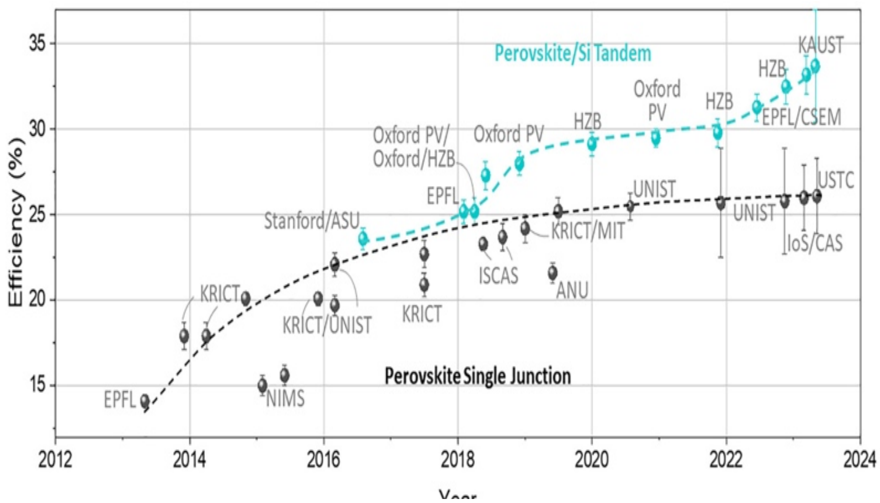


Figure 3 Efficiency of perovskite cells (single and tandem) over the last ten years with the research elements making efficiency breakthroughs. [H]

Traditional solar cells capture energy using a single side (monofacial) pointed at the sun. Unitizing both sides of a panel (bifacial) captures direct sunlight on the front and reflected sunlight on the rear, increasing energy captured by a single array.[H] Along with gathering extra energy from light that reflects off surfaces and hits the back of the tiles, these advanced solar cells made of perovskite are designed to work with less light to start generating electricity, producing more overall energy.[H] Additionally, a bifacial panel that tracks with the sun makes up to 45 percent energy gain over static systems.[M] However, bifacial systems face complex production challenges. However, historical research and development investment in original panels points to a similar rapid development in advanced solar cells.[M] The ability to capture a high percentage of energy and track solar pathways increases efficiency, lowering overall footprint.

Rigid, fragile materials make up traditional solar, creating panels unsuitable for mobile and rapid deployment configurations. Flexible versions provide durability and deployment options. Current advances in flexible options demonstrate an efficiency rate of 32 percent, similar to their rigid counterparts.[M] Additionally, the arrays maintained more than 80 percent of their initial efficiency after 1,000 bending cycles.[M] These flexible cells are lighter, create more power for their size, and can be put on diverse surfaces. They can also be tailored to specific sizes and shapes for different jobs.[H] The versatility and efficiency of the flexible panels increased their applicability in the military domain, making them durable and deployable.

Large-scale production, manufacturing, and durability performance of high-efficiency solar panels face many challenges. The primary challenge involves solving the durability issues and long-term panel stability.[H] Substantial investment by both the private sector and government research grants seeks to unravel this issue, with the federal grants specifically investing in stability, durability, and survivability in extreme conditions.[M] Due to the sensitive nature of these panels, large-scale manufacturing remains challenging. For example, slight temperature differences during production dramatically impact efficiency.[H] Furthermore, the manufacturing base must develop cost-effective cell production environments capable of minimizing variations in development.[H] Despite these challenges, the United States Solar Energy Technology Office developed sources of capital to invest in research and development for high-risk startups to accelerate the development and production of perovskite cells.[H]

Analytical Confidence

The analytic confidence for this estimate is *moderate.* Sources were generally reliable and tended to corroborate each other. There was adequate time, but the analyst worked alone and did not use a structured method. Given the extended timeline for this estimate, this report is sensitive to change due to new information, such as production breakthroughs and increased fossil fuel costs.

Author: LTC John M. Oliver

Efficient, Lightweight Hydrogen Fuel Cells are Highly Likely Available by 2035

Executive Summary

Efficient, lightweight hydrogen fuel cells capable of providing energy for large vehicles or small buildings are highly likely (71-86%) to be available in 10 years due to comparatively low requirements for rare earth elements, high energy efficiency, and high commercial versatility. Fuel cells generate electricity from hydrogen with no carbon emissions. Their quick refueling ability and efficiency make them suitable for heavy or long-range vehicles. Despite the push for decarbonization across multiple sectors, the high cost of hydrogen production, storage limitations, and current infrastructure may challenge the adoption of this technology.

Discussion

Hydrogen fuel cells convert the chemical energy of hydrogen into electricity through an electrochemical reaction with oxygen, creating energy. The reaction produces electrons that flow to an external circuit, allowing for the use of electrical power or storage for later use. This reaction requires a small number of raw materials, with platinum being the rarest and the primary cost driver.[H] However, unlike many other rare materials, platinum is recyclable, making it a more sustainable and viable long-term rare earth material.[H] Additionally, researchers are actively pursuing a replacement for platinum, often considered the weak link in the chemical reaction, due to its high cost and rarity. Within the last year, researchers produced a precious metal-free cell system with similar qualities to the platinum version.[H] Lithium batteries, generally considered the competitor for fuel cell vehicles (FCV), require numerous precise metals. Additionally, the extraction of metals negatively impacts the environment. The primary lithium deposits in Chile, Argentina, Australia, and China lead to supply chain bottlenecks and make the resource vulnerable to geopolitical tensions.[M] Green power generation systems that rely on a few rare earth raw materials have an inherent cost and supply chain advantage for adoption.[M]

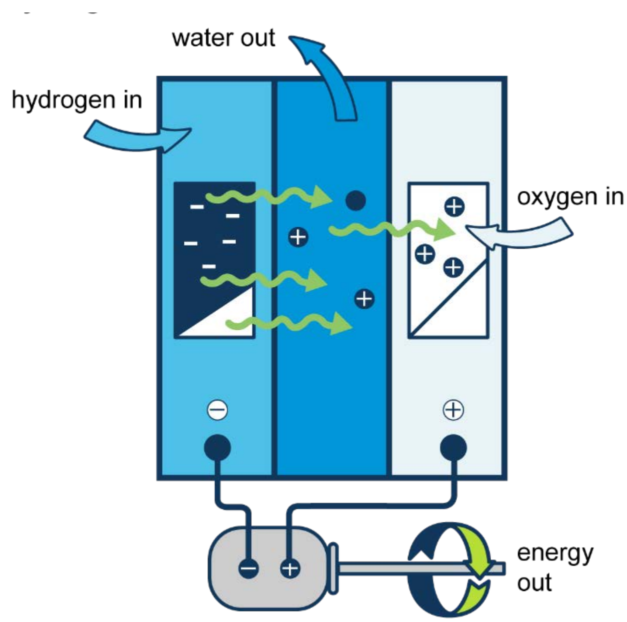


Figure 4- Chemical Reaction of a Hydrogen Fuel Cell [H]

Electrochemical cells boast exceptional weight and energy density efficiency, yet they are typically larger than lithium batteries. Larger vehicles that can fit a hydrogen fuel cell travel farther before needing a refill compared to those with batteries. Hydrogen is energy efficient for its weight, which means vehicles using it can travel up to 300 miles without refueling.[H] FCVs can refuel quickly, similar to traditional internal combustion engine vehicles utilizing a pump. In contrast, especially large batteries may require considerably more time to recharge.[H] Fast refuel, coupled with the ability to handle heavier payloads compared to batteries, is why major automotive manufacturers are looking at hydrogen fuel cells to replace diesel fleets.[M] The high energy efficiency and fast refueling will increase the deployment of hydrogen fuel cells in markets dominated by diesel fleets.

Fuel cells can provide power for extremely large applications. They offer high versatility and can serve markets where batteries are impractical, such as shipping. Most studies on shipping decarbonization point to cells as the primary power generation alternative.[M] Moreover, factors such as retrofitting increase the scalability. Approximately 43% of ships traveling from the U.S. to China can be retrofitted with electrochemical cells with minimal adjustments.[M] The flexibility goes beyond vessels, with Boing investing in H_2 cells to replace jet power engines for its future fleet.[M] Boeing successfully tested this replacement engine in 2023 and plans a test flight in 2026.[M] GM is actively developing a mobile generator concept that utilizes fuel cells for rapid deployment.[M] Hydrogen fuel cells can replace large diesel combustion engine systems, making them a viable alternative for extremely large vehicles. This commercial applicability and relative success of prototypes will drive market investment in this capability as government regulations restrict carbon emissions in the transportation industry.

Fuel cells have various challenges that may hinder adoption at a larger scale in the next few years. The primary issue revolves around infrastructure, with current investment focusing on electric battery recharging. Currently, there are only 59 retail hydrogen stations in the U.S., most of them in California.[H] Additionally, clean hydrogen production is expensive on small scales due to the limited production quantities. To address these issues, the Biden administration unveiled extensive tax credits for the industry in December of 2023.[M] The H_2 also faces high-density storage challenges (i.e., refueling stations). The size of the tanks required remains an obstacle, but the Department of Energy created a technology office to develop solutions.[H] The adoption challenges for fuel cells center around the logistics support rather than the technology. As technology progresses and fuel cells emerge as the most efficient green energy source for large vehicles, airplanes, and sea vessels, targeted investment can overcome the barriers to adoption.

Analytical Confidence

The analytic confidence for this estimate is *moderate.* Sources were generally reliable and tended to corroborate each other. There was adequate time, but the analyst worked alone and did not use a structured method. Given the extended timeline for this estimate, this report is sensitive to change due to new information, particularly federal investment in a hydrogen supply network.

Author: LTC John M. Oliver

Section 2: Assured Energy

Advancements in Battery Thermal Management on Course to Enable Carbon-Free Energy Transition by 2035

Executive Summary

Advancements in Battery Thermal Management (BTM) are highly likely (71-85%) to enable safe and efficient energy storage by 2025, which is necessary to support the Army's carbon-free energy reliance plan. These advancements are pivotal for mitigating risks associated with high-capacity batteries, integral to the strategic shift toward more sustainable and resilient energy sources. By addressing the thermal management challenges, these technological innovations will enhance the safety and efficiency of battery storage systems and align with objectives to improve energy security by adopting carbon-free technologies.

Discussion

A Battery Energy Storage System (BESS) is a sophisticated technology that plays a pivotal role in the modern energy landscape, particularly in enhancing the reliability and efficiency of renewable energy sources and providing critical backup power. At its core, a BESS stores electrical energy in battery cells during periods of excess generation or low demand. [H] Stored energy in the batteries is then utilized during peak demand times, outages, or low generation previously built up in the systems. The ability of a BESS to store and dispatch energy on demand makes it a key component in stabilizing the electrical grid, reducing reliance on fossil fuels, and facilitating a transition to renewable energy sources. [H]

An effective Battery Thermal Management System (BTMS) is significant, especially for large batteries used in BESSs. Due to their size and energy density, large batteries are prone to thermal risks such as overheating, which can lead to reduced efficiency, degradation of battery life, and, in extreme cases, safety hazards like thermal runaway. Thermal runaway is a condition where an increase in temperature changes the conditions in a way that causes a further temperature rise, often leading to catastrophic failures. [H] [H] An effective BTMS ensures that the battery operates within an optimal temperature range, enhancing the battery's lifespan. It does so by actively managing the heat generated during charging and discharging processes, which is particularly crucial during periods of high demand or rapid charging scenarios, where the risk of overheating is significant. [M] By maintaining the battery temperature within a safe and efficient range, a BTMS safeguards the battery against potential thermal dangers and ensures consistent performance and reliability. BESS reliability is essential for applications requiring a dependable energy supply during production downtime and in remote locations away from production facilities.

Innovations in phase change materials (PCMs), liquid cooling, and BTMS for fast charging/discharging applications in grid-scale energy storage are at the forefront of advancements. These technologies become crucial in addressing solutions to thermal management challenges posed by the high energy densities and rapid charging requirements in modern batteries, which have become essential to renewable energy systems and electric vehicles. Researchers focus on PCMs' ability to absorb and release large amounts of heat during phase transitions, stabilizing battery temperatures during peak loads. [H] Engineers concentrate on improving liquid cooling systems that use coolants to transfer heat away from battery cells, aiming to enhance efficiency and reduce the complexity of BTMS. Experts expect that over the next 10-15 years, advancements in BTMS technologies will evolve to meet the growing demand and requirements for producing and fielding carbon-free energy solutions. By improving battery

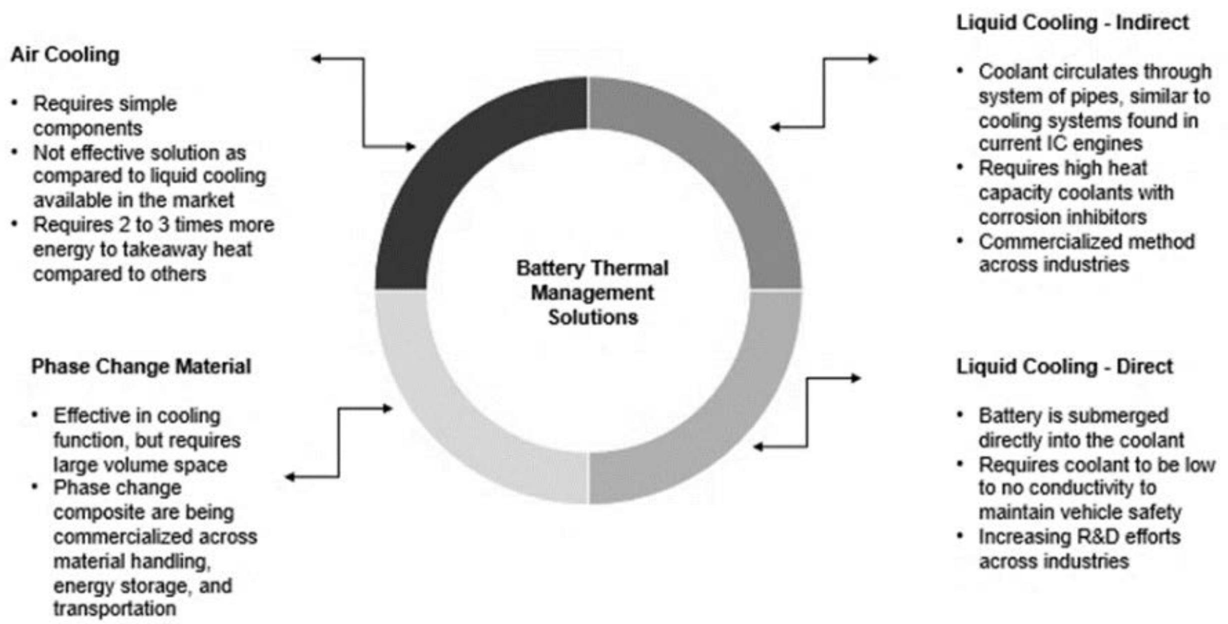


Fig 1: Battery Thermal Management Solutions

systems' efficiency, safety, and lifespan, BTMS innovations will play a crucial role in enabling the large-scale adoption of renewable energy sources. [H]

Despite the significant strides made in BTMS and their integration into large-scale energy storage systems, several challenges that doubt their readiness in the next 10-15 years still need to be addressed. Cost implications of adding thermal management, power electronics, safety measures, and controls to battery packs and systems can result in a two to fourfold increase in costs. [M] This cost escalation poses significant barriers to the widespread deployment of BTMS in large-scale grid applications where economic viability is a critical factor. Additionally, the fragmented and unorganized nature of the energy transition, along with raw material scarcity and production bottlenecks, combine to raise concerns about the ability of BTMS to meet the safety and efficiency demands of the future, potentially slowing the transition to a carbon-free energy solution. [M]

Analytical Confidence

This estimate has high analytical confidence. The sources were reliable and tended to corroborate with one another. The analyst worked alone and did not use a structured method. Artificial Intelligence facilitated topic outlining, problem scoping, and sourcing reliable scientific and scholarly articles.

Author: COL Luke Clover

Electric Vehicles are Highly Likely to be Utilized as Energy Sources in Expeditionary Conditions

Executive Summary

The U.S. Army is highly likely (71-85%) to depend on electric vehicles (EVs) as the primary energy storage solution for command posts in the field and expeditionary conditions as it transitions to carbon-free energy sources. EVs will become more than just transportation and combat assets; they will become multi-purposed as energy storage and discharge solutions capable of powering command and control posts, eliminating the need for additional batteries and reducing command structure footprints.

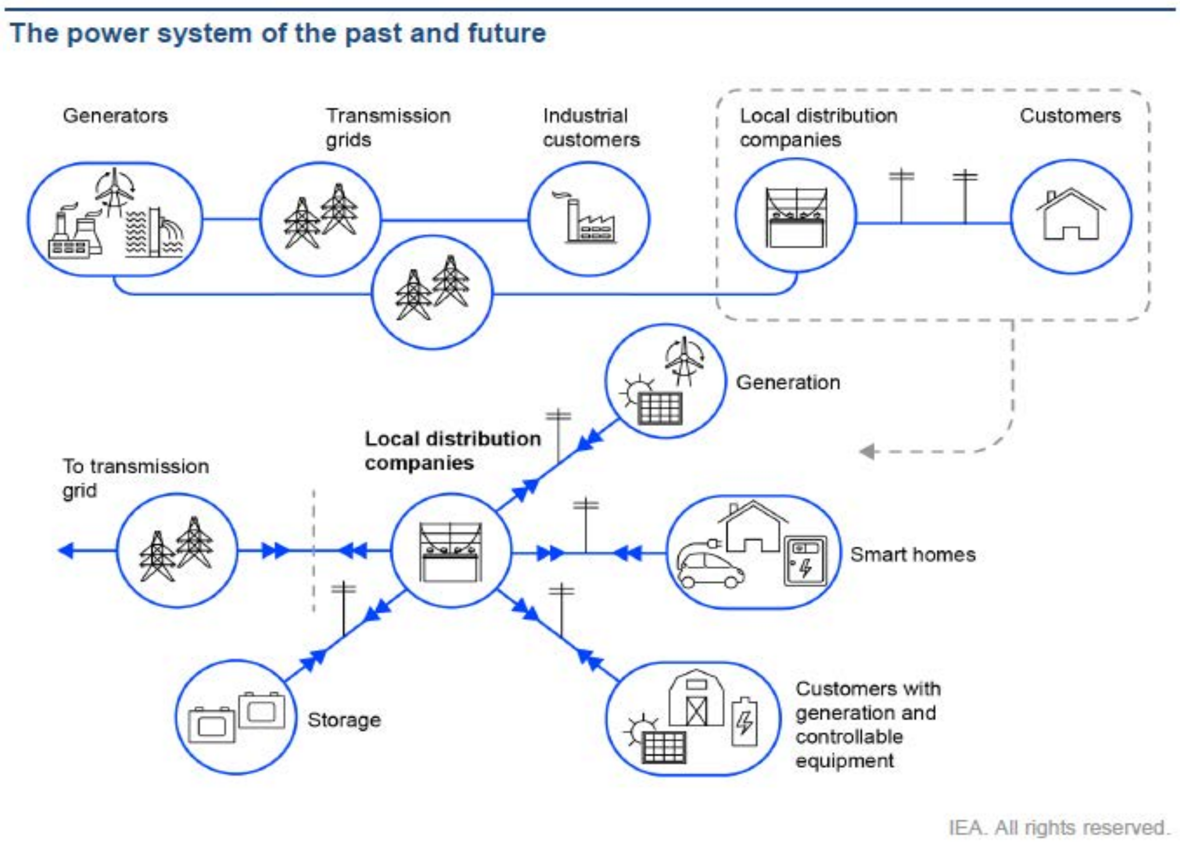
Discussion

As the U.S. Army plans the power transition to carbon-free energy solutions, outside-of-the-box thinking will take center stage. Future energy sources will be less energy-dense and more easily transported than fossil fuels. Creative energy storage solutions are needed to maintain easily transported and minimized footprints for mobile expeditionary command and control centers. Considered the energy storage solution of the future, battery banks will play an essential role in powering command posts on the battlefield. However, large banks are heavy, hard to transport, and often unreliable when scaled to meet grid requirements. By looking at emerging technological innovations in the energy sector, the military may be able to solve several challenges with one solution. [H] The shift toward EVs in the military will transcend merely transportation and combat capability; it is highly likely to provide mobile energy storage capable of accepting excess production when available and providing electrical supply when needed.

The power grids of the past were a one-way flow, with energy moving from generation to transmission lines to distribution services down to the customer. The future will work more in a unidirectional flow where decentralized power sources will reduce the reliance on a sole commodity. [H] Dynamic supply and demand are at the center of intelligent grids equipped with artificial intelligence to anticipate energy needs and adjust supply accordingly. This two-way flow of electricity between supply points and demand nodes unlocks an abundance of benefits, reducing reliance on traditional hydrocarbon energy stores and the gaps limiting renewable energy production. It is a profound technological transformation that will revolutionize energy distribution, resilience, and sustainability, which the U.S. Army and the Department of Defense will look to as it modernizes its installations, vehicles, buildings, and generating assets.

The use of EVs as a potential power grid resource and battery solution is supported by three major characteristics: their operational flexibility, in that they can both charge and discharge; embedded communications and control technologies so they can respond quickly to grid requirements; and low-capacity utilization, as they are stationary more than in operation in expeditionary environments. The state of California is studying and testing the utilization of EVs as a bridging solution for power grids, given the state's high ownership level, giving lots of data points and testing opportunities fueling this advancement. H

Of course, challenges remain. Battery energy density and charging infrastructure require further development to fully harness the potential of EVs as primary energy storage solutions that can feed back into the power network. But the path forward is clear; the military has eyed electrifying its future, and EVs are leading the charge, as it turns out, not just on the battlefield or supply routes but also in powerfully redefining the essence of expeditionary operations.



Source: Adapted from IESO (2019), Exploring Expanded DER Participation in the IESO-Administered Markets

Analytical Confidence

The analytical confidence in this estimate is *high*. The sources used to draft it were reliable, professional, and corroborated one another. There was adequate evidence and time, but the analyst worked alone and did not use a structured method. Given the extended time horizon of this estimate, this report is sensitive to emerging technological advancements and information.

Author: COL Luke Clover

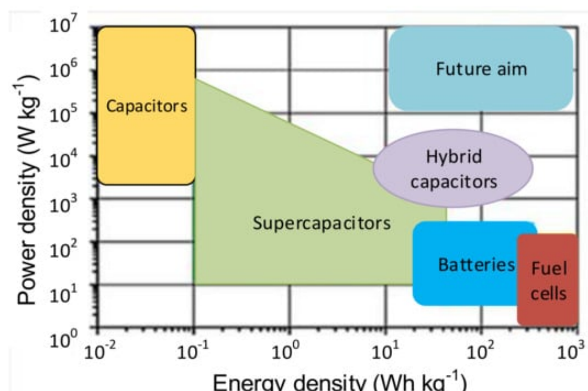
Supercapacitors Will Highly Likely Become a Primary Energy Capture and Storage Solution Across Applications by 2035

Executive Summary

Supercapacitors (SCs) will highly likely (71-85%) be vital to energy storage by 2030 due to their ability to regulate energy generated by wind and solar power and their utility in personal use devices and electric vehicles (EVs). Despite their relatively low energy density compared to batteries and fuel cells, SCs are well suited for powering wearable and implantable devices and communications devices due to their ability to provide bursts of energy required for signal transmission and quick charging and discharging.[M]

Discussion

SCs have large storage capability in materials that have significantly less environmental impact than batteries, operate in temperature extremes not tolerated by other storage mechanisms, and have a superior number of charge/discharge cycles as compared to battery storage, making them ideal for storing energy produced by wind and solar power.[H] Energy outputs from carbon-free sources such as wind, solar, or tidal energy are inherently unpredictable due to environmental factors. Fluctuations in energy output limit the lifespan of batteries, driving up costs and increasing the risk of interruptions in service.[H] SCs are capable of storing large amounts of energy in mediums that are more accessible and which have a lower environmental impact than other storage mechanisms.[H] SCs do not require rare and/or potentially polluting materials such as lithium, cobalt, or nickel. Rather, they use carbon compounds readily available from incinerating biomass and other, less environmentally damaging metals and metal oxides.[H] MIT researchers created an SC by mixing carbon black and cement, allowing the foundation of a house to store the equivalent of one day's supply of electricity.[H] SCs are capable of hundreds of thousands of charge/discharge cycles and operate at extreme temperatures, ensuring that they can store energy in the austere climates where many green energy platforms are located.[H]



Comparison of the energy and power density of storage devices.[M]

The proliferation of small electronic devices such as smartphones, implantable medical devices, radios, and remote sensors requires lightweight, reliable, and sustainable power. Such devices tend to have low power requirements or operate in short bursts of energy when transmitting a signal.[H] The cost savings of SCs versus lithium-ion energy storage are considerable, and the supply chain is more secure because they are made of readily available materials. This technology allows energy capture from human movement, opening opportunities for power generation via mechanical suits or other wearables already in future soldier programs.[H]

SCs are used in various transportation applications, including EVs, trains, and e-bikes. Despite their ability to store large quantities of energy, they are not suited as the sole source of power for most transportation needs.[H] It is highly likely that they will have an increased role in personal use transport (e-bikes, scooters, etc.) by 2030 based on cost savings and lower environmental impact as compared to battery power.[M] SCs in tandem with batteries help extend the life of EV batteries and providing added power for acceleration.[H] Improving SC design will likely allow them to give a more significant share of the energy in EVs, improving vehicle performance and service life.

Analytical Confidence

The analytic confidence for this estimate is *high*. The analyst was not time-constrained and did not use a structured method to develop the report. The analyst did not collaborate on this estimate; however, the estimate falls within the range of reasonable opinion. Sources were reliable and corroborated one another. The time horizon for this analysis is lengthy, and the report is sensitive to change due to new information.

Author: COL Stacy L. Moore

Significant Improvements to Batteries Almost Certain by 2035

Executive Summary

More stable, energy dense, longer lasting, and environmentally friendly energy storage devices are almost certain (86-99%) to be commercially available by 2035. They break down into three broad categories: improvements on existing LI storage, batteries using technology similar to LI but that replaces lithium with other elements, and novel designs.[HM] Despite not totally eliminating environmental or supply chain concerns, the cost savings, less risky supply chains, and limited environmental impacts of new batteries are driving industry to produce them at scale to replace current LI storage solutions.

Discussion

Lithium-ion (LI) batteries are used in nearly all commercial applications due to their high energy density and technological maturity.[H] Despite this, they have detrimental effects on the environment, from ecological degradation caused by mining to hazardous waste at the end of their useful life. [H] Traditional LI technology is also challenged by sub-optimal charge/discharge cycles, slow recharging, fire risks due to low thermal tolerance, and supply chainscontrolled by some of the US's biggest rivals. [HH]

New generation LI batteries use advanced materials that allow greater lithium storage on positive and negative electrodes to produce greater energy density, faster charging, long lifetime and cycling performance, and better temperature operating ranges.[H] Scientists are using silicon anodes to increase energy capacity in one application and replacing cobalt with more readily available sulfur in a different battery.[M] These improvements have corporate backing, with products expected for use in EVs and consumer electronics by 2031.[M] Upgrading existing LI batteries could capitalize on current commercial architecture, speeding this product to market. It would also allow makers to produce more power with the same amount of rare earth metals. Despite not reducing the environmental footprint or providing a less risky supply chain, this technology is highly likely to make its way into consumer products due to its superior performance.

LI storage technology uses rare earth metals like lithium, cobalt, and nickel.[H] China, the US' strategic competitor, processes many of these elements while others come from conflict zones, such as the Democratic Republic of Congo.[H] Technologies replacing lithium with other more common elements seek to eliminate the supply chain issues inherent with current batteries and create a smaller environmental footprint. Batteries using sodium, manganese, and other metal oxides, in combination with advances in anode and cathode science, promise to produce similar storage capacity and energy density and improved lifecycles and safety.[MM] Despite current designs falling short of the performance metrics associated with LI batteries, this technology is highly likely to be incorporated in commercial systems due to cost savings from reduced rare earth metal use and the ability to use existing facilities for production.

Some battery designs do not rely on a liquid electrolyte to conduct energy. Solid-state batteries use solid electrodes and a solid electrolyte to create higher energy density, lower risk of fire, and potentially higher mileage for EVs.[M] While some solid-state batteries use lithium, scientists created one with a mix of titanium, zirconium, tin, hafnium to create similar results to LI solid-state batteries without the problematic supply chain.[M] Iron-air batteries also use a process akin to rusting in reverse, leveraging oxidation to store energy.[H] This technology is best suited for stationary applications due to low energy density and it is already in production and in use in several US power plants.[H] Another advancement best suited for stationary uses is flow batteries. These batteries use large tanks of liquid electrolytes to store energy. They have a high energy density, a long life cycle, and a quick response time.[M] Other technologies using unique materials such as graphene, glass, gold and other precious metal nanotubules and silicon are in development.[MM] While promising, it is unlikely that they will overtake the above batteries by 2035 due to the need to develop new manufacturing facilities.

Analytical Confidence

The analytic confidence for this estimate is *high*. The analyst was not time-constrained and did not use a structured method to develop the report. The analyst did not collaborate on this estimate; however, the estimate falls within the range of reasonable opinion. Sources were reliable and corroborated one another. The time horizon for this analysis is lengthy, and the report is sensitive to change due to new information.

Author: COL Stacy L. Moore

Hybrids and EVs Likely for the Army's Heavy Vehicles by 2035

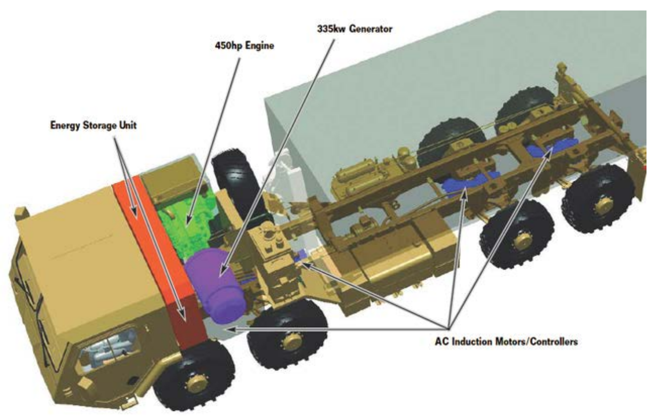
Executive Summary

The decarbonization of heavy-wheeled vehicles in the US Army is likely to be dependent on a dual-effort approach incorporating hybridized and fully electrified drivetrains. Despite advances in the field, ongoing shortfalls in power capacity continue to impede full electrification and may require a bridging strategy that is more likely to succeed by 2035 and beyond.

Discussion

OSHKOSH Defense provides the Army's heavy ground transport requirements almost exclusively with their Heavy Expanded Motility Tactical Truck (HEMTT A4) and Heavy Equipment Transporter (HET).[H] The HEMTT is capable of a combined (payload w/trailer) tow capacity of 22 tons with an operational range of 300 miles. [H] The HET provides increased capabilities (70 tons/523 miles), being the only tactical vehicle able to transport the M1 Abrams Tank. [H] Efforts to electrify such platforms continue but face limitations with operational endurance. Engineers are unable to replicate the power density and efficiency within diesel engines, even with today's most sophisticated batteries. [H] Additional factors such as cargo weight, armor plating, and temperature extremes further exacerbate diminishing returns from onboard power systems.

With full electrification of its heavy combat vehicles deemed infeasible, OSHKOSH experimented with hybridized versions that incorporate a 450 HP diesel engine and 480 VAC induction drive motors. Now designated as the ProPulse Hybrid Diesel-Electric System with Export Power, the system seeks to increase overall fuel efficiency by 20 percent while providing up to 100kw of exportable AC power. [H] Despite the lack of full electrification, this platform remains important for two reasons: it maintains a practical program for development as the industry continues to advance the field of electrification (e.g. energy storage, transmission, and propulsion), and it enables a bridging strategy between diesel and full electrification with the added benefit of exportable power for command centers, C2 nodes, and other smaller EV platforms.



The ProPulse Hybrid System applied to a HEMTT

In addition to its tactical requirements, the US Army relies upon commercial heavy-wheeled platforms to operate within garrison environments. Whether through organic MTOE equipment or service contracting, the Army is dependent on semi-trailer trucks and other heavy cargo assets to sustain its logistics functions. In contrast to combat platforms, advances within the civilian sector are more likely to electrify these vehicles. Capitalizing on its success with EVs, Tesla has developed the Semi– a fully electrified tractor-trailer able to tow 40 tons with a range of 500 miles. [H] It can recharge up to 70 percent of its energy capacity within 30 minutes. PepsiCo, the first organization to incorporate EV semi-trucks within its distribution network, has acquired 21 Semis to augment its traditional diesel vehicles. [H] Initial feedback from sustained use reports positive performance and reliability. [M] PepsiCo invested in EV infrastructure by procuring four Tesla chargers, each with a capacity of 750 kilowatts, totaling 3 megawatts of installed charging capacity. [H] Thus, the company sustained a high operations tempo without the limitations of lengthy recharging periods. The apparent success of PepsiCo should be noted by any organization looking to decarbonize its logistics footprint. [H] The alternative for not doing so may relegate electrification as a niche capability so long as petroleum-based fuels remain relatively inexpensive and abundant. [H]

PepsiCo's prudent investment in recharging infrastructure

Analytical Confidence

The analytic confidence of this estimate is *medium* based on an assessment of technological maturity and the lack of widespread heavy EVs in the mainstream. The available research on the full electrification of tactical heavy vehicles remains sparse. Research on ProPulse technology dates to NOV 2006 suggesting marginal progress – even with hybridization, to the present day. [H]

Author: LTC Eric Soler

Advancements in Propulsion will Almost Certainly Transition the US Army towards Electrification of its Light/Medium Utility Fleet by 2035

Executive Summary

Ongoing developments in defense automotive capabilities should almost certainly provide the momentum needed to meet the service goals of an all-electric non-tactical vehicle (NTV) fleet by 2035, and fully electric tactical platforms by 2050. The US Army operates significant quantities of wheeled vehicles ranging from commercially available fleets to its High Mobility Multipurpose Wheeled Vehicle (HMMWV) and Family of Medium Tactical Vehicles (FMTV). [H] Despite the technical challenges associated with environmental durability and energy management, ongoing efforts to electrify light/medium wheeled platforms such as GM's Infantry Squad Vehicle (eISV) now demonstrate the technical maturity needed to feasibly achieve the Army's vision above. [H]

Discussion

The emergence of Tesla Inc. over the last 20 years began with its first low-volume, production "Roadster" sports car in 2008. The company would continue to hedge towards full electrification of consumer-accessible electric vehicles leading to a 2023 annual revenue of $96.8 Billion with over 4 million vehicles produced. [H] Perhaps taking a cue from Tesla's success, GM would experiment in electrification with varying levels of success in its hybrid drive-train technologies (combining a gasoline engine with w/electrified drive motors) found in the Chevrolet Bolt and other "EV" models to follow. Benefiting from GM's research and development in electrification, its subsidiary GM Defense would later adapt the technology into its ISV platform, which is based on the Chevrolet Colorado ZR2 with Duramax 2.8 turbo diesel I4 engine. [H]

The Electric Infantry Squad Vehicle (eISV) with Cargo Box

The further developed, all-electric eISV vehicle is equipped with an eCrate 400V 3-Phase AC Permanent Magnet Motor with a High voltage GM BEV2 lithium ion Battery rated at 400V 66kWh. [H] Specific performance metrics such as weight/cargo capacity and range remain unavailable due to ongoing testing. Still, the company indicates "travel distances similar to those of internal combustion engine solutions." [M] To provide a benchmark for analysis estimation, a roughly similar platform can be assessed with GMC's Hummer EV, recently brought to production for the civilian market. An optionally maxed-out model with "Ultium Drive" architecture (24 Cell Pack) can tow up to 12,000 lbs with a 570-hp dual-motor powertrain with a 381-mile range. [M] However, feedback from real-world consumer experiences reveals reduced performance parameters depending on load capacity, weather variables, and availability of fast vs slow charging capabilities. A noteworthy highlight regarding shortcomings of electrification was demonstrated in New York as newly acquired Garbage Removal Trucks could not satisfactorily perform secondary roles as snowplows as their use was restricted to four hours due to degradation of their power cells from load and extreme cold. [H]

Despite their successful debut on the civilian market as a viable method of transportation, the technology “does not exist to generate, store, and distribute electric power in a tactically relevant amount of time. [M] Further technological refinement is required to increase hydrocarbon fuels' energy density and portability. Additionally, significant acquisition decisions must be made to define requirements, allocate funding, and establish formal programs of record for the Army enterprise. Recent expenditures of $47.8 million on electric vehicles in FY22, $78.4 million in FY23, and a request for $270.6 million in FY24 show progress, but there is still inadequate investment from the Department of the Army. [M]

Analytical Confidence

The analytic confidence of this estimate is *high* based on documented technological results within commercial activities, the defense industrial base, and real-world observations with electrified vehicles. Sources utilized were mostly based on official government publications and industry technical documents. Personal observations of several Tesla vehicle fires may have created some level of bias during my research – but were mitigated with scientific facts.

Author: LTC Eric Soler

Section 3: Smart Tech Synergy

3D Printed Buildings Likely Potential for Installations or Expeditionary Bases by 2035

Executive Summary

3D printed buildings have a likely construction potential for installations or expeditionary bases by 2035 due to reduced construction time, lower labor costs, and fewer required resources and waste generation. Despite the high costs of printing, scale restrictions, and lack of standardization in the US construction industry, the use of 3D construction printing presents a sustainable and cost-effective option for future installations or expeditionary infrastructure.

Discussion

3D construction printers have proven to be efficient and speedy in their operation, resulting in reduced construction times. Traditional construction methods can be time-consuming, leading to an increase in job-site accidents. Using 3D printing technology, construction time can be reduced by up to 50 percent, leading to cost savings and shorter timelines for occupancy.[H] In 2014, China constructed the world's first 3D-printed five-story apartment building within 45 days, which possessed enough structural strength to withstand natural disasters in an earthquake-prone area.[M] Printer technology advancements will decrease construction times and labor requirements, making it an alternative solution for the US Army to rapidly develop installations, military construction projects, or forward basing.

The construction industry heavily relies on human labor, which can account for at least 25 percent of total project costs.[H] Additionally, unskilled labor can lead to delays and project extensions. However, according to a report by Markets and Markets, 3D printing has the potential to significantly reduce construction waste by 30–60 percent, lower labor costs by 50–80 percent, and decrease construction time by 50–70 percent. A study conducted in Jordan also found that 3D printing could reduce material costs by 65 percent compared to traditional construction methods[H], thereby lowering overall human labor costs and requiring fewer resources. In 2014, Dubai built a fully functional 2700-square-foot office building in just 17 days, reducing projected labor costs by 50 percent.[H] Current 3D construction printing technology has already demonstrated its ability to lower labor costs, and this trend is expected to continue over the next 10-15 years as technology and efficiency continue to improve.

The amount of construction waste generated globally will reach an estimated 2.2 billion tons annually by 2025. Half of this waste will be made up of building materials such as wood, shingles, asphalt, concrete, and gypsum.[H] Unfortunately, construction is responsible for 40 percent of the world's carbon dioxide emissions.[H] While 3D printing cannot solve all the problems associated with construction waste, it can certainly help reduce the amount of wasted resources. 3D printing is an additive manufacturing process that uses exactly the required amount of material to create a structure.[M] This automated process is computer-aided and requires fewer human resources, as well as no tooling and dies/formwork. As a result, this method reduces manual processes, labor requirements, and material waste.[H]

3D construction printing faces several challenges that must be addressed to enable larger growth and employment in future construction projects. The technology is more expensive than traditional construction methods due to the high operational costs of printers. Additionally, creating the digital model required for safe and cost-effective construction can be expensive. However, industry stakeholders can minimize these costs by forming collaborative partnerships with technology providers or sharing access to printing facilities.[H] The large size of printers also poses challenges, including difficulties in site placement and higher costs.[H] Current printers can only produce minor to medium-sized building components, which may not be practical for larger projects with limited spaces.[H] To address this issue, a hybrid approach combining 3D printing with conventional techniques is required to achieve the appropriate scale and size for a project. The 3D printing industry lacks updated regulatory practices and construction codes that are familiar across the board.[H] Traditional building codes were not designed for 3D-printed structures, which creates uncertainty over compliance, liability, and other legal ramifications that limit its use. To address this issue, the US construction industry is exploring new initiatives that involve cooperation between regulatory agencies, business organizations, and construction professionals.[H] These initiatives aim to create standardized procedures for larger market opportunities and ensure compliance with updated regulations.

Analytical Confidence

The analytic confidence for this estimate is *moderate*. The analyst was not time-constrained and did not use a structured method to develop the report. The analyst did not collaborate on this estimate; however, the estimate falls within the range of reasonable opinion. Sources were reliable and corroborated one another. The time horizon for this analysis is lengthy, and the report is sensitive to change due to new information.

Author: COL Erik C. Oksenvaag

Battery Storage Highly Likely to Enable Installation Energy Resilience by 2035

Executive Summary

Battery storage is highly likely to enable installation energy resilience by 2035 due to reliable backup power, microgrid integration, and electric vehicle infrastructure. Storage systems are a potentially transformative technology for installations to generate resilient and self-reliant energy. Despite the current challenges of battery safety, accurate battery monitoring, and capability balances, storage technology is indispensable in developing future sustainable and efficient installations.

Discussion

Traditional grid systems struggle to meet increasing demands resulting in power outages and disruptions. Battery storage offers a solution by providing reliable backup power for installations. Renewable energy accounted for 30 percent of global electricity in 2020, with a continued increase in demand for the coming years.[H] Storage enables better integration of renewable sources with means to store excess energy generated during low-demand periods.[H] This technology enables load balancing by storing power during off-peak hours and supplying it during peak demand.[M] This creates optimization by reducing reliance on peak-demand power and creating energy cost reductions. Installations can create independence from centralized power grids and diversify their energy sources to enhance resilience.

Storage is a critical component of microgrids enabling efficient energy management and integration of renewable energy sources. Climate Central reported that 83 percent of all reported power outages from 2000 to 2021 were weather-related events.[H] Colorado implemented microgrid resilience as part of their climate strategy to address growing concerns of weather-related wildfires and associated damages.[H] Microgrids can seamlessly provide emergency power to critical infrastructure and essential services during outages or natural disasters. Battery storage provides a stable and consistent electricity supply in microgrids and eliminates the potential of traditional grid system fluctuations that can result in power outages.[H] Efficient storage and microgrids contribute to reduced carbon footprint and independence from conventional power grids.

Battery storage is critical to the necessary infrastructure to support future electric vehicle fleets. The Army Climate Strategy aims to field an all-electric non-tactical vehicle fleet by 2035.[H] Charging stations with storage enable installations to overcome potential challenges of peak demand and grid congestion with a large electric fleet. Storage can increase the capacity of a charging station by storing excess electricity during low-demand periods and releasing it during peak hours. This excess electricity increases the output power of charging stations to optimize the charging process[M], and reduce the charging time.[H] Storage facilitates load management by alleviating strain on the power grid during peak hours, allowing for smoother integration of electric vehicles into the installation grid. In addition, this contributes to grid stability by absorbing excess energy when electric vehicle charging demand is low and supplying stored energy into the grid during peak hours.

Despite the practical application of storage for future installation resilience, battery quality, and design limit the long-term use of current devices. The majority of designs use lithium-ion components and have an average lifespan of ten years. When the voltage, temperature, and current exceed these batteries' maximum limitations, they are susceptible to catastrophic failure. In addition, accurate state-of-charge information is important to avoid overcharge and over-discharge which ruins maximum usable energy.[H] Battery packs consume current at different rates due to load variations. These variations lead to an imbalance in energy and lower the maximum useable energy of the whole battery storage. Imbalances worsen over the battery's life span, causing battery packs to age at different rates. Companies are developing systems to monitor and manage these aspects of batteries to prevent faults and failures.[H] Safe and reliable management systems mitigate the risk of current lithium-based batteries to extend storage life spans and increase safety. In addition, the capital costs of various components are likely to decline by approximately 60 percent by 2030, making replacement costs cheaper to exchange current battery storage for new emerging technology.[H]

Analytical Confidence

The analytic confidence for this estimate is high. The analyst was time-constrained and did not use a structured method to develop the report. The analyst did not collaborate on this estimate; however, the estimate falls within the range of reasonable opinion. Sources were reliable and corroborated one another. The time horizon for this analysis is lengthy, and the report is sensitive to change due to new information.

Author: COL Erik Oksenvaag

Smart Buildings Energy Management Likely to Impact Installation Construction by 2040

Executive Summary

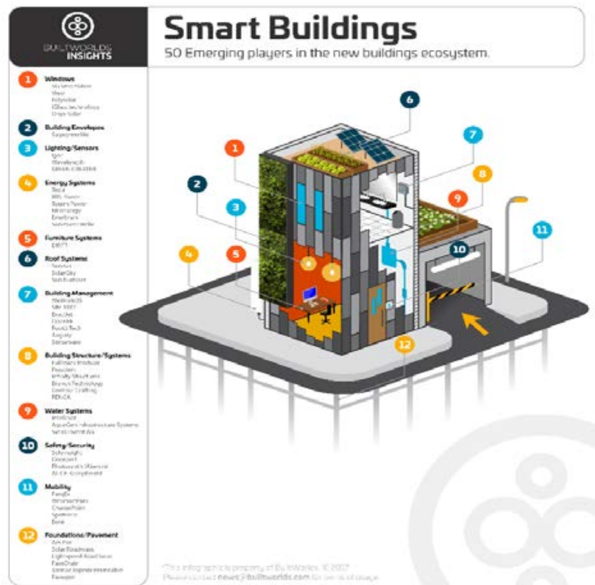
Smart buildings are likely to offer significant benefits by 2040 for installation construction due to improving energy efficiency, enhancing sustainability, and cost reduction. Improved power efficiency leverages automation and systems to significantly reduce energy waste. Enhanced sustainability reduces greenhouse gas emissions and electrical consumption helping to minimize a carbon footprint. Organizations can reduce costs by using data-driven decisions to optimize energy. Despite the growing trends of smart buildings in the civilian business sector, the high implementation costs, lack of standardization, and data security will make it unlikely for the military to incorporate them into military construction in the near future.

Discussion

Smart buildings use intelligent systems that track and control energy consumption in real time. Facilities expend an extensive amount of electricity for heating, cooling, lighting, and powering equipment. Many current buildings suffer from energy waste, inefficient systems, and outdated practices that result in unnecessary expenses and an increased environmental footprint.[M] The UN Environment Programme reports the building sector accounts for 40 percent of global energy consumption and 30 percent of greenhouse gas emissions.[H] In addition, the US Environmental Protection Agency estimates that commercial buildings waste 30 percent of their electrical consumption.[M] Smart buildings leverage advanced automation and intelligent algorithms that analyze electrical patterns and identify optimizations. These systems employ automated lighting controls, HVAC optimization, and power management to reduce waste.[H] Facilities that mitigate and control their energy waste enable greater efficiency and resilience, with up to 30 percent savings.[H]

Smart buildings create opportunities for enhancing sustainability in urban areas by integrating renewable energy into their power generation,[H] and reduces the reliance on traditional sources. For example, a CO2-neutral factory in Ludenscheid, Germany, integrates renewable energy and smart systems that generate 14 percent more electricity than needed and saves up to 630 tons of carbon dioxide annually.[H] The factory then sells the surplus back into the local grid thus being fully independent of traditional power.[H] AI and machine learning enhance building performance through dynamic power scheduling, predictive maintenance, and power management to reduce waste.[M] Blockchain technology enables decentralized electrical transactions and enhances transparency, which results in energy sharing and waste reduction. Smart buildings will become an integral component of a larger grid that can facilitate optimized distribution and load balancing[H], increasing the environmental sustainability of military installations.

Smart buildings create substantial cost savings and assist in identifying energy waste resulting in lower utility expenses. Fully implemented digital systems demonstrated a 30 percent reduction in costs for heating, lighting, and appliances.[H] Real time tracking and data analysis allows for predictive maintenance and power redistribution, allowing facilities to avoid expensive emergency repairs. One large commercial facility spent USD 5.1 million on Maintenance and USD 3.7 million on Utilities annually.[M] Their smart building program reduced annual maintenance costs by up to 10 percent and annual utilities cost by up to 20 percent, and saving USD 1.25 million annually in operating expenses.[M] Energy costs are a significant expense for organizations, but smart building technology creates an opportunity to reduce expenses and reprioritize cost savings toward other installation projects.



Smart building technology has current challenges that may prevent the military from implementing them on installations. Management solutions can be costly and time consuming for retrofitting current structures. While the perception of initial costs is high, calculating the long-term savings can help justify the investment. Installations can start with smaller projects as a pilot to test feasibility and assess potential benefits. In addition, implementation costs can be offset by using available grants, subsidies, or energy efficiency programs.[H] Smart building technology lacks uniform standards and protocols with integration and compatibility issues from competing vendors and technologies. Focusing on interoperability ensures seamless integration of various systems from vendors with proven track records. Also, installation managers can develop an open architecture with a modular and scalable system allowing for future technology upgrades and expansion.[H] Data security is vital to avoiding data breaches and protecting smart building digital architecture. Installation G6 staff or the Network Enterprise Centers will play a crucial role in updating software and encryption protocols, and network segmentation to protect systems from adversaries. Installations can mitigate these risks and challenges to create future opportunities for significant energy efficiency, enhancing sustainability, and cost reductions.

Analytical Confidence

The analytic confidence for this estimate is *moderate*. The analyst was not time-constrained and did not use a structured method to develop the report. The analyst did not collaborate on this estimate; however, the estimate falls within the range of reasonable opinion. Sources were reliable and corroborated one another. The time horizon for this analysis is lengthy, and the report is sensitive to change due to new information.

Author: COL Erik Oksenvaag

Data Analytics Highly Likely to Enable Installation Energy Stability by 2035

Executive Summary

Data analytics is highly likely to enable installation energy stability by 2035 due to managing grid optimization, enhancing grid stability, and improving demand response efficiency. Data-driven energy systems offer insights into grid operations, usage patterns, and demand response strategies. Despite the challenges of data volume and network interoperability, effective data analytics enhances installation stability and ensures a reliable power supply.

Discussion

Data analytics offers installations the essential tools to manage grid optimization. Grid optimization refers to the process of enhancing the efficiency, reliability, and resilience of the grid. Artificial intelligence (AI) and machine learning techniques can analyze vast amounts of energy consumption, production data, and patterns to optimize microgrid operations.[H] Real-time monitoring reduces operational downtime and improves resource allocation across the grid. It identifies anomalies in voltage fluctuations, power outages, or equipment failures, enabling a quick response to prevent or minimize downtime.[H] Pacific Gas and Electric Company reduced outage durations by 25 percent by utilizing data analytics from over nine million smart meters.[H] Data analytics enables accurate load forecasting by predicting power demand patterns based on historical data, weather conditions, and time. This allows optimization of power generation and distribution, ensuring reliable energy supply and avoiding wastage.

Data analytics techniques help installations make informed decisions and take proactive measures to maintain grid stability. Grid stability refers to the ability of a microgrid to maintain its voltage and frequency within acceptable ranges.[H] Data collection identifies patterns and anomalies that can cause grid stability vulnerabilities.[H] The grid equipment and infrastructure's condition is monitored in real time, enabling a preventive maintenance approach that reduces the chances of equipment failure and maintains a consistent power supply. According to an Electric Power Research Institute study, data analytics predictive maintenance can reduce maintenance costs by up to 40 percent and extend the lifespan of equipment by 20 to 25 percent.[H] Additionally, analytical prediction of potential grid failures based on historical patterns, weather data, and real-time information enables preventive measures such as load shedding or rerouting power to prevent outages. Japan's largest utility company, TEPCO, uses data analytics for energy distribution and potential failure detections, achieving a 15 percent reduction in power losses and a 20 percent improvement in energy efficiency.[H] Leveraging data analytics techniques enhances energy efficiency and improves reliability, creating predictable grid stability.

Data analytics plays a crucial role in improving the efficiency of demand response, which involves managing and balancing electricity supply and demand effectively.[H] Traditional methods rely on historical data and forecasts to estimate and plan for electricity demand. However, this approach often leads to inefficiencies and imbalances, resulting in higher costs and energy wastage.[H] Research shows that implementing analytics in smart grids can result in up to 15 percent of energy savings, reducing greenhouse emissions and promoting sustainability.[H] In addition to energy savings, data-driven technologies can also reduce operating and maintenance costs by over 12 percent.[H] The use of real-time data analysis optimizes energy operations and reduces costs.

The energy sector is becoming increasingly digitized, resulting in a surge in data volume and the need for data quality. While data analytics can help improve energy stability in installations, challenges such as data volume, network interoperability, and seamless communication among grid components and control systems remain. The key to addressing these challenges is to standardize grid components, invest in advanced communication technologies, and develop scalable data management systems and analytics tools.[H] However, it is equally important for installations to invest in their workforce through education, partnerships, and certification programs.[H] Educational institutions can offer specialized programs to equip students with the necessary skills for microgrid operations. Public and private partnerships can create a robust workforce through internships, research, and knowledge exchanges. Industry-recognized certification programs can validate grid professionals' skills and knowledge, creating opportunities for career advancement and leadership positions. By investing in the training and education of their workforce, installations can mitigate a host of technological challenges and prepare for a future of reliable and consistent energy.

Analytical Confidence

The analytic confidence for this estimate is high. The analyst was time-constrained and did not use a structured method to develop the report. The analyst did not collaborate on this estimate; however, the estimate falls within the range of reasonable opinion. Sources were reliable and corroborated one another. The time horizon for this analysis is lengthy, and the report is sensitive to change due to new information.

Author: COL Erik Oksenvaag

Advanced Technology in Cooling Systems Likely to Drastically Cut Energy Demand by 2035

Executive Summary

Variable Refrigerant Flow (VRF) systems are likely (56-70%) to reduce energy requirements for heating and cooling systems by 50-60 percent in the next decade. This expected reduction is attributed to continued technical advancements in efficiencies in the area and continued financial benefits to the business sector as governments and organizations strive to reduce greenhouse emissions. Key efficiency drivers in the technology are the capability to heat and cool different zones simultaneously with the same compressor and condensing unit and variable speed servo motors that operate at only the required levels necessary based on the thermal load.

Discussion

As technological innovations progress, it is almost certain (86-99%) that governmental enacted energy efficiency mandates for appliances and facility mechanicals worldwide will elevate. The heating and cooling industry is at the forefront of sectors poised to impact global energy consumption in the future. The General Services Administration (GSA) reports that heating, cooling, and air handling mechanisms are responsible for approximately 33% of energy usage in U.S. commercial buildings. [H] VRF systems offer numerous advantages over traditional Heating, Ventilation, and Air Conditioning (HVAC) units, leading to their growing popularity for new construction installations and existing structural retrofits. The increased adoption of these systems in commercial buildings, coupled with realized financial gains from sales, suggests that continued advancements in energy efficiency in this style of HVAC systems are highly likely (71-85%) to continue over the next 10-15 years.

VRF systems are characterized by high energy efficiency and fewer moving parts, resulting in lower operational costs. These systems operate only when necessary and at the required capacity, minimizing wear and tear on components and reducing the frequency of breakdowns and downtime. VRF systems achieve heightened energy efficiency through two primary mechanisms: heat recovery variations of the system that extract heat from zones requiring cooling and repurpose it for zones needing heating, and variable speed motors that adjust compressor speed based on the current heating/cooling load. [H] Although initial procurement costs for VRF systems are higher than those for traditional rooftop units (RTUs), the energy efficiency gains typically yield a return on investment within five years. Compared to more conventional commercial air handling units, VRFs require fewer wall penetrations and reduced operational space, as they utilize refrigerant pipes for small individual room units instead of large air ducts pushing and pulling large volumes of repurposed air. The efficiency benefits of this style of air handling are twofold. First, it alleviates possible cross-room contamination of recycled air amongst zones, and second, it alleviates heating or cooling losses realized in air ducts from centrally located condensers and air handlers in mechanical rooms.

A controlled case study comparing VRF and RTU systems revealed significant energy savings with VRF technology during cooling and heating seasons under full and partial load conditions (100%, 75%, and 50% thermal loads). During the cooling season, the VRF system achieved estimated energy savings of 30%, 37%, and 47%, respectively. In the heating season, the savings were 51%, 47%, and 27% at the respective thermal load conditions. [H] These observed energy savings are poised to increase in the coming years as continued advancements in refrigerant

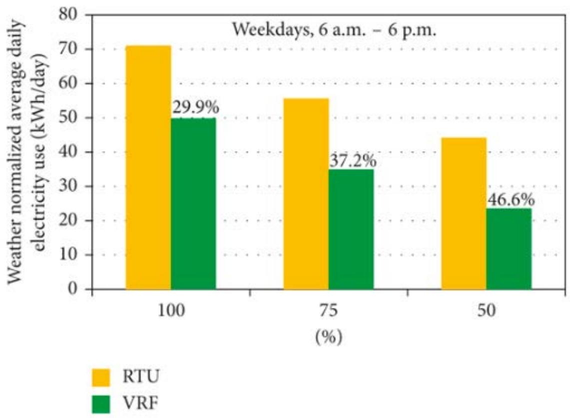


Figure 1. VRF versus RTU efficiency in cooling

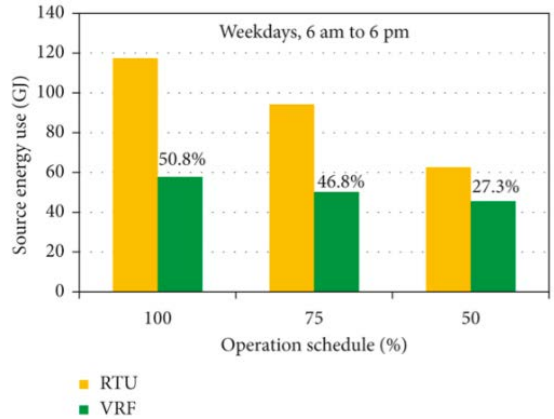


Figure 2. VRF versus RTU efficiency in heating

routing and heat recovery progress.

Energy efficiency is a prerequisite for decarbonization, and VRF systems are poised to contribute significantly to the commercial and residential structures sector. As strategic electrification expands worldwide, energy-efficient air handling options such as VRF can substantially impact lower utility usage by eliminating combustion heat generation models and implementing heat recovery and reuse solutions. [H] Despite base VRF technology being several decades old, continued advancements and innovations keep it at the cutting edge. As the Department of Defense (DoD) seeks to integrate more renewable energy sources into its installations and expeditionary locations, the technological advancements in VRF systems offer a promising avenue for reducing reliance on carbon-based fuels and progressing toward a future net-zero carbon footprint.

Analytic Confidence

The analytic confidence for this estimate is *moderate*. Sources were reliable, numerous, and corroborative. There was adequate time, but the analyst worked alone and did not use a structured method. The analyst used artificial intelligence to identify reliable sources and to copy-edit the final product.

Author: COL Luke Clover

Section 4: Obstacles

Rare Earth Elements Availability Likely to Disrupt Green Technology by 2035.

Executive Summary

Rare Earth elements availability is likely (56-70%) to disrupt green technology by 2035 due to resource competition, geopolitical dependencies, and environmental concerns. Rare Earth Elements (REE) are critical components of climate change technologies, including batteries, solar panels, and wind turbines. Despite the significant investment in mining and the global push for de-carbonization, the scarcity, locations of deposits, and difficulty extracting minerals will constrain availability.

Discussion

By 2035, the demand for rare earth elements will increase by over 200 percent.[H] The supply will not be able to keep up with the demand, leading to expected shortfalls by 2030, and it is anticipated that these shortfalls will widen by 2035.[H] Lithium, an essential for battery production, is the primary driver of the anticipated shortages. Increasing the supply to address shortfalls presents further challenges. Although the Earth's crust contains abundant rare earth elements and they are distributed globally, only areas with large, accessible deposits can support economically viable mining. [M] Establishing mining operations is time-consuming and capital-intensive. With large concentrations in only a few locations worldwide, the capacity to scale up mining and increase supply remains challenged.

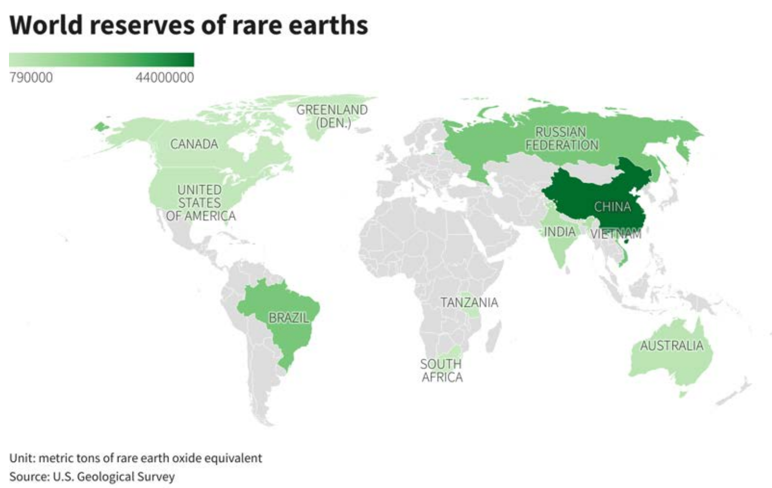


Figure 5: Location of rare earth elements[H]

The Western world relies primarily on Russia and China for rare Earth elements, which creates strategic vulnerabilities and dependencies and enables supply and price manipulation. These two countries extract most of the current supply, with China producing over 60 percent of the world's yearly exports.[H] With increasing demand for these elements, Russia and China can manipulate the market, slowing production or raising prices to achieve strategic political goals. China currently incorporates export restrictions and production permitting requirements to control the flow globally, similar to how the Organization of Petroleum Exporting Countries controls oil supply.[M] China imposes manufacturing restrictions on many elements, pressuring the relocation of manufacturing to China and creating additional dependency.[H] The United States Department of Defense's increasing focus on green technologies for military use intensifies the challenge, as these elements are located in adversarial countries. This geographical concentration of critical materials poses a strategic risk by potentially allowing these nations to control the supply.

Current mining practices of rare Earth elements create significant environmental impacts. Mining practices require digging large pits and utilizing large amounts of water and toxic chemicals for extraction.[H] The byproduct of this process is waste ponds that cause water pollution and detrimental impacts on local ecosystems.[H] Advanced countries, aware of the environmental impacts of mining, imposed restrictions on the practice within their borders. The U.S., despite having mineral reserves, operates only one rare earth mining facility that continually faces environmental pressure to close.[H] European countries with deposits often do not extract them due to ecological impacts and proximity to cities. Additionally, a congressional research report analyzed electric vehicle raw material extraction versus the production of an internal combustion vehicle engine and found that the greenhouse gas emissions are 1.3 and 2.3 times higher for raw materials extraction.[H] The ecological effects of current mining practices and mineral development will limit supply expansion and constrain supply to current mining in countries willing to overlook the impacts.

Despite the significant investment in mining and the global push for decarbonization, the inability to scale sustainable mining and finance new operations will limit the increases in supply. Several companies, such as ExxonMobil, have developed drilling methods for extracting lithium with a lower environmental impact.[M] These companies are initiating operations in the United States and other Western countries. However, battery makers learned that developing and financing a mineral mine takes over ten years.[M] The time between capital investment and initial output creates financing barriers for mine development. This results in the U.S. government becoming the primary financier for new projects.[H] However, since financing is required for almost a decade, the inherent volatility of U.S. political budgets creates additional hurdles.

Analytical Confidence

The analytic confidence for this estimate is *high*. The analyst was time-constrained and did not use a structured method to develop the report. The analyst did not collaborate on this estimate; however, the estimate falls within the range of reasonable opinion. Sources were reliable and corroborated one another. The time horizon for this analysis is lengthy, and the report is sensitive to change due to new information, particularly new element finds and technology breakthroughs.

Author: LTC John Oliver

Green Technology Transition Barriers Likely to Delay Industry Adoption by 2035

Executive Summary

Green technology transition by 2035 will likely (56-70%) face disruptions due to competition costs with fossil fuels, power transmission, and switching costs. Shifting to green technology from carbon-producing energy sources requires changing infrastructure, power generation methods, employment specialization, and industry priorities. Despite technological investment and a global push for decarbonization, history shows that transitioning to new energy sources is time and capital-intensive.

Discussion

While green technology costs are decreasing, solar power installation remains costly at USD 2 thousand per kilowatt for large systems and 3.7 thousand per kilowatt for residential grids, compared to 1 thousand per kilowatt for new gas-fired plants.[M] For capital-intensive products, this creates an economic incentive to stay with fossil fuel technologies. Current market conditions are more favorable for oil and gas production, which yields nearly 20 percent on profit margins.[M] In contrast, green energy projects typically see profits between 5 and 10 percent.[M] These companies strategically invest in areas such as hydrogen and lithium, where they hold competitive advantages without immediately challenging their core oil and gas operations.[H,M] With structural and economic incentives currently favoring fossil fuels, scaling up new green power generation remains challenging.

The U.S. must boost its power transmission capacity by 60 percent by 2035 to address the rising demand for green energy.[H] This expansion is necessary to accommodate the dispersed setup of renewable energy sources like wind and solar farms, often far from existing power grids. The U.S. should establish an extensive network for the transmission of green energy. The significant drop in mileage of newly built transmission lines from 2000 miles during 2012-2016 to just 700 miles in the past four years is evident.[H] Local challenges arise from communities' increasing opposition to these projects due to concerns about land use and the costs that local authorities must cover, as well as objections from regional power generators controlling the current market.[H] The Department of Defense in the United States will encounter challenges related to power transmission at its posts and bases as it undertakes the modernization of outdated infrastructure. As a significant energy consumer, detaching from local power supplies will financially impact existing energy providers.

Transitioning to new technology involves financial outlay and addressing problems such as consistent power supply, the mathematics of adoption, and existing policies. These elements are part of the overall switching costs. Many sources of green energy depend on variable environmental conditions, leading to an intermittent power supply that can disrupt continuity or necessitate large-scale battery systems to maintain consistent electricity.[M]
The sheer scale of energy adoption required poses a significant long-term barrier to decarbonization. Beyond financial investment, aligning the power, manufacturing, construction, and transportation sectors presents structural challenges to the broader adoption of green technology.[M] The energy sector's current regulatory policies and processes are complex and

lengthy, often giving an advantage to established industries.[H] These transition costs will make adopting emerging technology locally and switching at Army posts problematic.

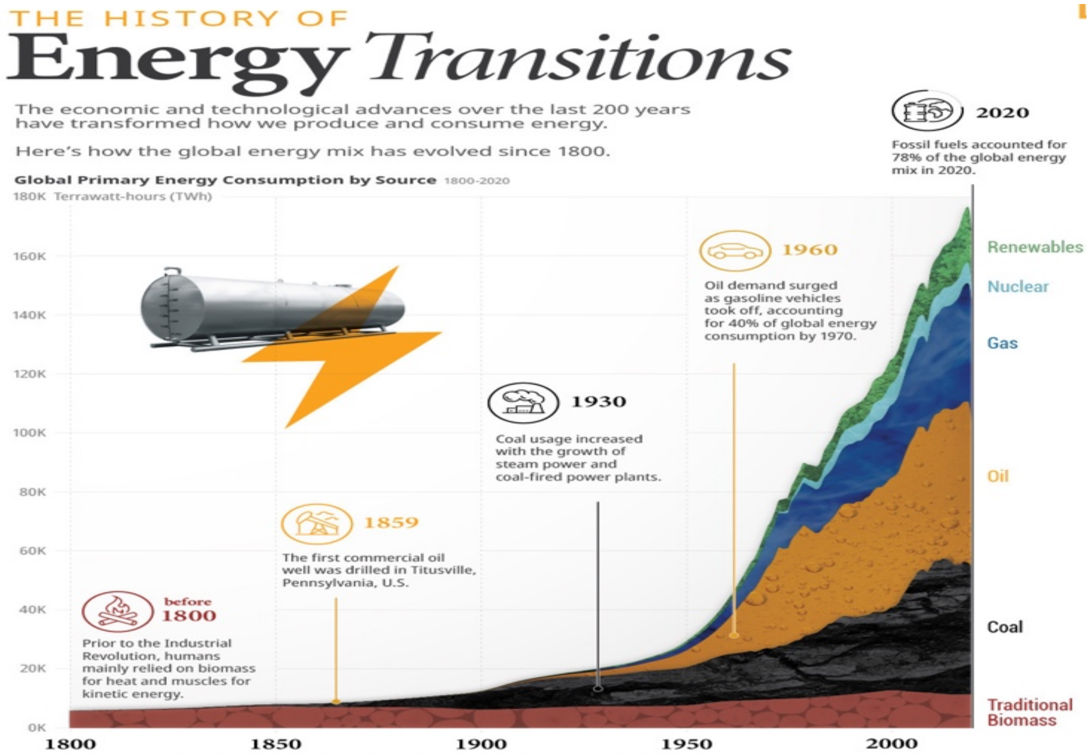


Figure 6: History of Energy Transition[H]

Despite the significant investment in green energy and the global push for decarbonization, the history of energy transition shows that transitions take a long time and are energy additions rather than eliminating previous energy sources.[H] The railroad industry underwent a gradual shift from steam to diesel engines, a process that spanned approximately 70 years, starting with the prototypes of diesel engines and ending with their complete adoption.[H] However, the adoption of diesel engines did not significantly accelerate until World War I and the rise in prominence of internal combustion engines in automobiles.[H] The gradual shift was due to companies' reluctance to adopt new technologies and the railroad industry's hesitancy to move away from the synergistic benefits of transporting and using coal, which was a major source of profit.[M] However, the adoption of diesel engines did not significantly accelerate until World War I and the rise in prominence of internal combustion engines in automobiles.[H] Energy transitions require time, as entrenched systems and organizational barriers can impede swift change. To facilitate these shifts, concerted efforts from organizations and governments are necessary to overcome these challenges.

Analytical Confidence

The analytic confidence for this estimate is *high*. The analyst was time-constrained and did not use a structured method to develop the report. The analyst did not collaborate on this estimate; however, the estimate falls within the range of reasonable opinion. Sources were reliable and corroborated one another. The time horizon for this analysis is lengthy, and the report is sensitive to change due to new information.

Author: LTC John M. Oliver

Lack of Skilled Workers and Facilities Will Highly Likely Impact the Use of Electric Tactical Vehicles through 2040

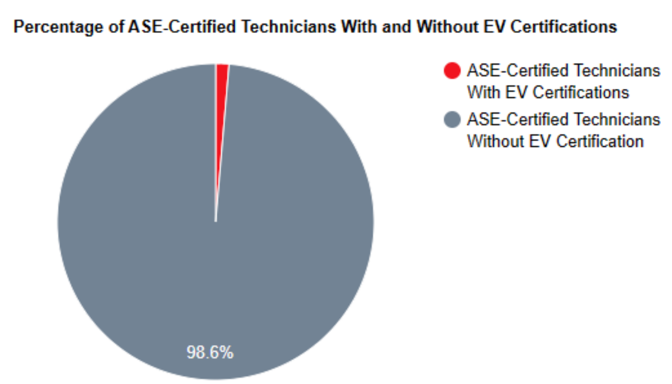
Executive Summary

Lack of skilled workers will highly likely impact the use of electrified tactical vehicles (ETVs) through 2040 due to recruiting difficulties, training, and required lead time for military construction. The Army failed to meet recruiting goals since 2014[H], falling short by ten thousand recruits for 2023[M]. The need for both ETV and legacy fleet maintenance beyond 2035 increases the complexity of training, causing training for mechanics and operators to likely fall short of required maintenance tasks. Despite the rapid development of electric technology in the civilian sector, budget and appropriation cycles will make it unlikely that the military will capitalize on the developments quickly.

Discussion

The US jobs market is projected to remain strong through 2032[H], making it highly likely that the challenging recruiting environment will continue. Despite the recent success of Army programs preparing recruits for entry into service, cultural factors such as decreased propensity to serve, decreased eligible recruiting pools, and increasing ideological divides in the population will continue to hinder recruiting efforts.[M] The lack of adequate manpower reduces the availability of soldiers for both on-the-job training and formal training in the skills necessary to maintain ETVs. This is highly likely to impact the overall readiness of the ETV and legacy fleets in spite of the Army's strong emphasis on materiel readiness. Despite the decreased maintenance requirements for civilian electric vehicles (EVs) leading to the need for fewer technicians to maintain EVs, it is unlikely that the military will be able to reduce its manpower significantly. Overall, force levels are highly likely to remain stagnant or fall, while workloads associated with high equipment readiness will climb between now and 2040 as the DOD incorporates ETVs into its fleets.

Units struggle to maintain internal combustion engine (ICE) fleets with current levels of training as evidenced by readiness challenges at combat training centers.[2] There are not enough experienced mechanics in the Army to instruct junior personnel on best practices and improve readiness across platforms. The Army Ordnance School teaches mechanical theory and platform-specific tasks for the current inventory. It does not teach ETV maintenance in any of its courses as of January 2024.[H] Changing course curricula takes up to two years, provided that the Ordnance School can source the appropriate instructors.[3] Military Occupational Skills training



Percentage of Automotive Service Excellence (ASE) Certified EV Technicians, *Automoblog, November 2023*[M]

[2] Author direct experience and interview with Senior Sustainment trainer at the National Training Center

[3] Interview with CSM Jason Decker, Former Command Sergeant Major of the Ordnance Corps

for ETVs will likely not emerge until at least 2026. Widespread fielding of Tactical Vehicle Electrification Kits (TVEKs) begins in 2027.[H] Training mechanics will be crucial to operating this new equipment. Despite the availability of civilian training, few repair technicians have electric vehicle certifications.[4] While civilian certification courses are increasing, only 3,100 technicians are currently certified leaving few options for contracted repair of military ETVs through 2040 due to the increased demand to repair civilian EVs.[H]

The Army's military construction (MILCON) budget fell from USD 6 billion in 2009 to 600 million dollars in 2017 as the service prioritized operational readiness over facility construction and maintenance.[H] Budget reductions left a backlog of facility maintenance across the enterprise, resulting in a 70 or less percent fully mission-capable rate for facilities across nineteen installations studied between 2007 and 2017.[H] Depots across the DoD are in a similar state, with all sites rated fair to poor with little improvement between 2016 and 2022 despite legislation requiring increased investment in maintenance activities and the development of plans to improve the condition of structures.[H] The Army Climate Strategy Implementation Plan for fiscal years 2023-2027 does not include the construction of any maintenance facilities for ETVs.[H] The MILCON planning and execution process takes a minimum of five years to initiate construction.[H] These factors combine to indicate that while opportunities exist to capitalize on existing refurbishment and construction projects, it is almost certain that facilities to maintain ETVs will remain insufficient before 2040.

Analytical Confidence

The analytic confidence for this estimate is *moderate*. The analyst was not time-constrained and did not use a structured method to develop the report. The analyst did not collaborate on this estimate; however, the estimate falls within the range of reasonable opinion. Sources were reliable and corroborated one another. The time horizon for this analysis is lengthy, and the report is sensitive to change due to new information.

Author: COL Stacy L. Moore

Transition Costs Will Certainly Hinder Energy Transition Through 2035

Executive Summary

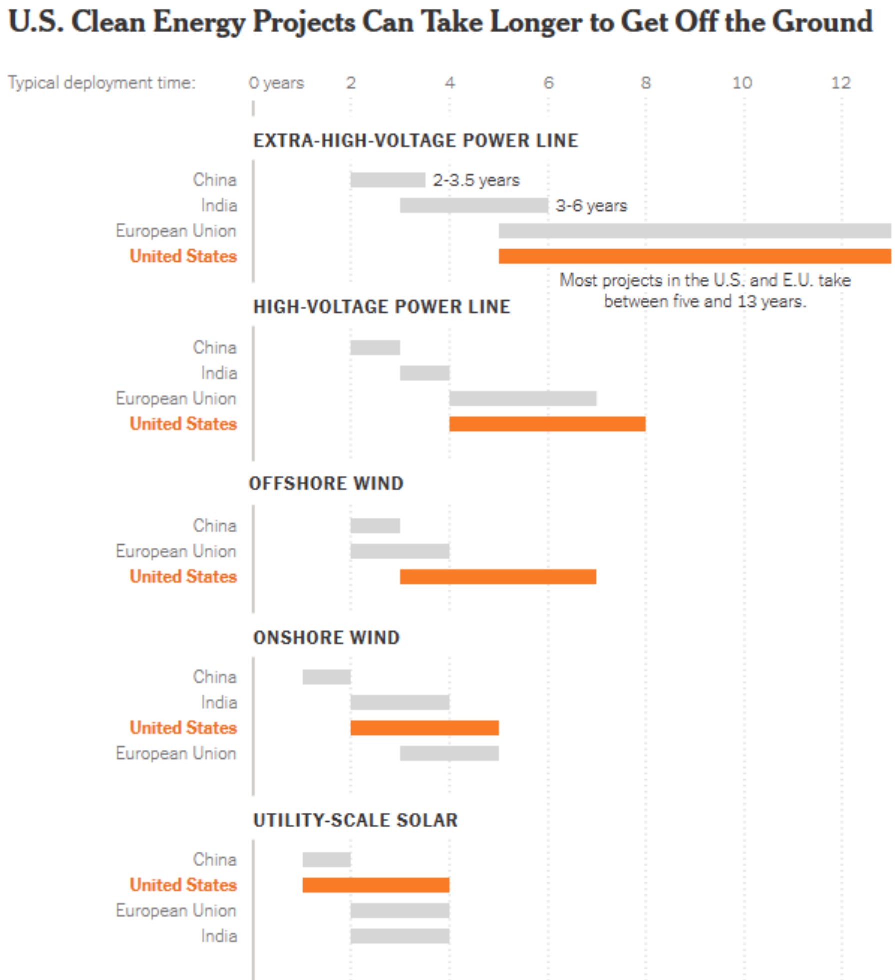
It is almost certain that the cost of building transmission lines local and regional policy decisions for zoning for green energy projects and will slow the transition to carbon-free energy through 2035.[H] The fractious nature of the US electric grid, competing market forces, and hard to navigate local policies and zoning laws will impact the ability for the US to increase solar, wind, and other environmentally friendly energy sources. Despite the large investment that the Biden administration made via the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA), issues inherent in the current energy supply system will slow the transition.[HM]

Discussion

The US electric grid consists of three regional grids that are not connected in ways that allow for the free flow of electricity among them. They are the Eastern, Western, and ERCOT (mainly the state of Texas) which further divide into twelve transmission planning regions, only six of which can transmit energy freely across regions.[H] The fragmented nature of the power distribution system is a major challenge to the green energy transition as wind and solar power do not provide constant energy flows throughout the day and are also highly seasonal.[HH] Wind and solar energy produce excess energy at certain times of the day and fall short of demands during others. In order to balance the grid, electricity must be able to flow from areas of excess to areas of shortage. Despite the disruption of energy supplies during winter storms in Texas and the Northeast and heatwaves in Texas in 2019 that cost hundreds of millions of dollars and put millions of people at risk, there is little movement in the regulation of regional grids to require them to enable energy sharing.[H] Increasing linkages between regions would make the system more efficient and resilient, not only providing a means to balance the grid from variable power sources, but also protect energy supply during natural or man-made disruptions. Creating opportunities for energy transfer must also include a way to pay for the transferred energy. It is possible for blockchain technology to ensure the provenance of the electricity and ~~ensure~~ that payment is made from the right consumer to the right producer.[H]

Electricity consumption was flat over the last 20 years, with energy efficient products making up for the growth in total electric consumers.[H] Investment by private industry typically follows growth in a sector, and with flat growth and the high cost of construction, it is unlikely that private firms will move to make improvements to the grid on their own.[H] Additionally, it is cheaper to build a combined cycle natural gas turbine power plant than a solar or wind farm, even though solar and wind have lower operating costs and are more resilient to petroleum price changes.[M] Despite the cost of green energy construction lowering over the last three years, the significant difference in up-front cost can deter investment.[M]

Over sixty-nine percent of respondents to a 2022 Pew Research study were in favor of the US becoming carbon neutral by 2050.[H] However, less than twenty-five percent were willing to live near a solar or wind farm and local laws restricting solar and wind power generation increased by thirty-five percent between 2022 and 2023.[MH] This is important because not only does it limit where green energy projects can be built, but it also increases the average time it takes to install these projects, slowing down the transition.[M] The time it takes to construct extra-high voltage power lines is particularly salient, as this component of the grid is vital to ensuring that the variability of green energy sources is smoothed throughout the system. Despite the negative consequences of local policies and zoning laws, there is little effort at the federal level to create a friendlier environment for new types of energy production.



Source: The International Energy Agency's World Energy Outlook 2022 · Notes: Ranges reflect typical projects commissioned in the three years prior to the publication of the I.E.A. report. By then, India had not completed any offshore wind projects. · By The New York Times

Analytical Confidence

The analytic confidence for this estimate is *high*. The analyst was not time-constrained and did not use a structured method to develop the report. The analyst did not collaborate on this estimate; however, the estimate falls within the range of reasonable opinion. Sources were reliable and corroborated with one another. The time horizon for this analysis is lengthy, and the report is sensitive to change due to new information.

Author: COL Stacy L. Moore

DoD Unlikely to Provide Sufficient Battery Recycling & Reconditioning Capability by 2035

Executive Summary

It is likely (56-70%) that the U.S. Department of Defense (DoD) transition toward carbon-free energy will face significant challenges due to the lack of battery recycling and reconditioning capability expected in the next ten years. The DoD's goal to reduce its carbon footprint significantly within the next 15-20 years is contingent upon the availability of facilities, technological advancements in large-scale recycling, and the costs associated with establishing and operating these facilities. The strategic importance of developing a robust battery recycling and reconditioning infrastructure impacts national security, environmental sustainability, and the military's ability to transition to carbon-free energy.

Discussion

The United States needs to improve and expand available battery recycling and reconditioning capability and infrastructure to meet expected future requirements associated with the transition to carbon-free energy. The limited number of commercial-scale recycling plants that handle the volume of batteries the DoD expects to generate creates a significant obstacle. While initiatives like the Battery Manufacturing and Recycling Grants Program aim to bolster domestic capabilities [H], the pace and scale of development must align with the DoD's timeline for transitioning to carbon-free energy. The technological complexity of recycling lithium-ion batteries, prevalent in military applications, requires significant advancements to achieve efficient, large-scale operations. Current recycling methods, such as hydrometallurgical and pyrometallurgical processes, are energy-intensive and must become more economically viable at scale. [H] The evolving battery chemistries and the need for specialized processes for different battery types add complexity to establishing a universally applicable recycling solution.

The financial implications of establishing and operating large-scale battery recycling and reconditioning facilities are substantial. Initial investments for constructing commercial-scale plants are expected to exceed 100-500 million USD [H], with additional costs for specialized equipment, permits, and skilled personnel. Facilities on the scale necessary to meet the expected needs of the DoD would drastically exceed those estimates. This might necessitate strategic collaborations through public-private partnerships and substantial institutional investments to jumpstart the industry. While federal funding initiatives provide some support, the overall financial burden may hinder the rapid development of the necessary infrastructure. [H]

The DoD faces several challenges and dangers in lithium-ion battery recycling and reconditioning, which could impact the future of carbon-free energy. Pyrometallurgy involves high-temperature processes to recover metals, which can be energy-intensive and generate harmful gases, posing environmental and safety risks. Hydrometallurgy uses chemical solvents to extract metals, requiring large quantities of potentially dangerous chemicals, which also presents ecological hazards and safety concerns for personnel handling these substances. [H]

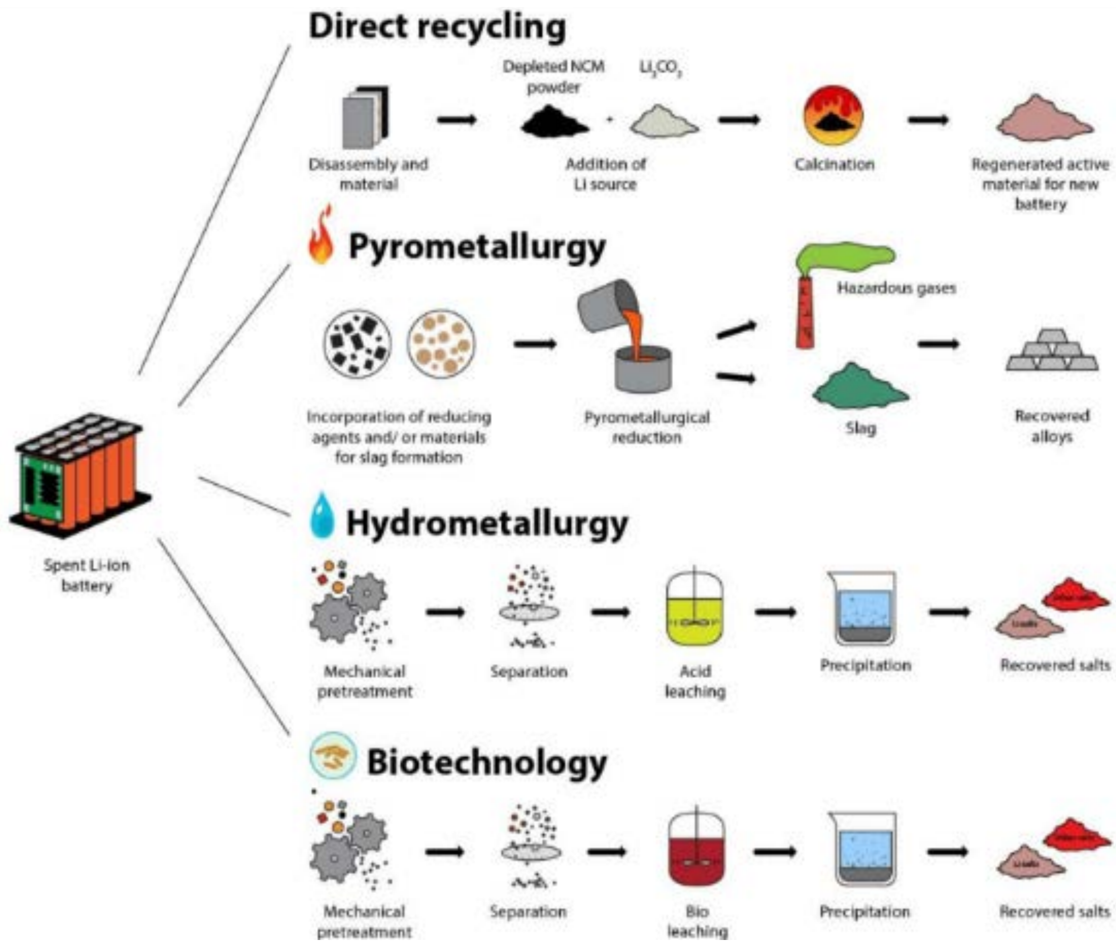


Figure 1. Typical direct, pyrometallurgical, hydrometallurgical, and biotechnological recycling methods for the recovery of Li-ion battery active materials.

The regulatory landscape for lithium-ion recycling is complex and evolving. The DoD must navigate federal laws such as the Resource Conservation and Recovery Act (RCRA), which governs the disposal of hazardous waste, including certain types of lithium batteries. Compliance with these regulations can be challenging and resource-intensive. [H] The handling and processing of lithium-ion batteries for recycling or reconditioning can pose significant safety risks to personnel. These batteries are known for their volatility and potential for thermal runaway, leading to fires or explosions if not managed correctly. Ensuring the safety of workers involved in the recycling process is a crucial concern that requires strict adherence to safety protocols, highly scientific intense practices, and proper training. Overcoming the technical and regulatory hurdles, ensuring environmental protection, and safeguarding the health and safety of personnel will be crucial for the successful transition to carbon-free energy sources by 2040. [H]

Despite these significant challenges, the strategic and environmental imperatives driving the DoD's transition to carbon-free energy sources underscore the necessity of overcoming these obstacles. Developing a robust battery recycling and reconditioning infrastructure is critical for the DoD's operational readiness and sustainability goals and for the broader national interests in securing a sustainable supply chain of essential materials and reducing dependence on foreign sources.

Analytical Confidence

The analytical confidence of this estimate is *moderate*. Sources were reliable and tended to corroborate one another. The analyst worked alone and did not use a structured method. Artificial Intelligence facilitated topic visualization, problem scoping, and sourcing reliable information.

Author: COL Luke Clover

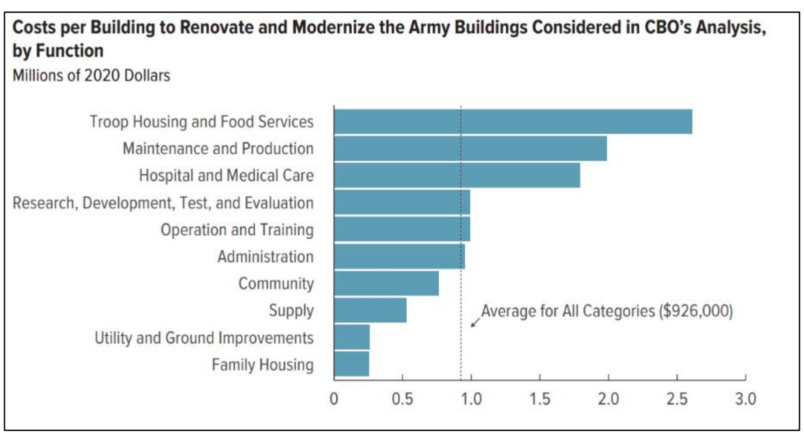
Infrastructure Costs Will Almost Certainly Hinder the Army's Decarbonization Efforts

Executive Summary

Transition expenditures will almost certainly (86-99%) hinder the Army's decarbonization efforts due to infrastructure costs, maintenance demands, and supply chain factors. Despite the goals set in the Army Climate Strategy and the Climate Strategy Implementation Plan, costs associated with upgrading infrastructure, maintaining legacy fleets, and supply chain factors are difficult to precisely forecast but will impact the ability to decarbonize the force.

Discussion

There is already a significant backlog of repair and renovation for buildings on military installations. This presents opportunities, as green energy technology could factor into renovation and new construction. The Army owns over 200 thousand buildings. A November 2022 report from the Congressional Budget Office analyzing repair and renovation costs for 49 thousand of Army buildings showed that it would take USD 19 billion to conduct all needed deferred maintenance and USD 34 billion to renovate these buildings to meet the usage needs of the units occupying them.[H] These figures do not take into account any upgrades associated with new equipment fielding. The report found that the types of buildings that Soldiers use most (housing, maintenance facilities, health care centers) have a higher-than-average cost of renovation compared to other building types.[H] In the fiscal year 2025 budget, there is nearly four billion dollars slated for military construction, with 2.4 billion dollars programmed for barracks upgrades, leaving little to address the nineteen billion dollar deferred maintenance shortfall, much less the cost of modernization and renovation.[M] There are significant costs associated with electric grids and other supporting structures that are not accounted for in military constructions costs. Despite the Biden administration's significant investment in clean energy infrastructure, the cost to renovate existing buildings and link them to power grids is certain to slow the transition to a decarbonized Army.[H]



2022 CBO Report: *The Army's Costs to Eliminate Its Deferred Maintenance Backlog and to Renovate and Modernize Its Buildings.*[H]

The Department of Defense Analysis of Alternatives Cost Estimating Handbook directs an analysis of alternatives when considering the new fielding of equipment that includes the costs associated with maintaining a legacy fleet of vehicles.[H] This handbook acknowledges that it is difficult to measure the full impact of switchover costs, as variables are unstable and many costs, like manpower and organizational energy are not easy to quantify. Despite the Army's current model of fielding equipment in unit sets, which lowers the costs associated with unit maintenance activities maintaining two fleets for more than a few months, there are still burdens to the unit and the Army during transition. Units expend considerable time and resources readying legacy fleets for turn in and must store and maintain repair parts for legacy fleets until they are directed to turn them in. Excess equipment is often not turned in during modernization and units move to other priorities, leaving legacy equipment and parts that require attention. Despite Army Materiel Command's creation of a Rapid Removal of Excess program in 2023, all installations have not been cleared of excess and it is unclear whether this program will be able to process the volume of equipment that will be generated by the transition to modernized combat platforms.[H]

There are costs associated with fluctuating market factors that will likely influence the rate of transition to green energy. The surge in global demand for batteries to power electric vehicles and store energy generated by wind and solar power are tightening the battery market, with some forecasters predicting that there will be a global shortage of batteries by 2027, leading to massively increased costs.[M] Even if there were no surge in global demand, the supply chains that contribute rare earth metals for the green economy are at risk because the raw materials are in countries in conflict or with unstable governments or are processed in nations that are US adversaries.[HM] There is evidence that green technology progresses faster when fossil fuel prices are high. Where the cost of coal or gas generated power is less than the cost to build green energy facilities, coal and gas tend to be the prevailing sources of energy.[M] If fossil fuel and coal prices were to drop significantly due to increased supply or falling demand, the economic case for green energy could shift, and the transition to carbon-free energy sources might stall.

Analytical Confidence

The analytic confidence for this estimate is *high*. The analyst was not time-constrained and did not use a structured method to develop the report. The analyst did not collaborate on this estimate; however, the estimate falls within the range of reasonable opinion. Sources were reliable and corroborated with one another. The time horizon for this analysis is lengthy, and the report is sensitive to change due to new information.

Author: COL Stacy L. Moore

Section 5: Other Findings

Significant Advances in Carbon-Free Energy Likely to Result from Public-Private Partnerships Within the Next Ten Years

Executive Summary

It is likely (56-70%) that the most significant advances in carbon-free energy transition will result from a public-private partnership (PPP) within the next 10-15 years. PPPs leverage the complementary strengths of both sectors by bundling capital investments, innovation, infrastructure capabilities, policy, influence, and regulatory control to accelerate technological advances. Key global examples of past PPPs demonstrate the model's effectiveness in driving rapid progress.

Discussion

Public-private partnerships allow governments to leverage private sector investments and financing to support large-scale renewable energy and carbon-free projects. This additional capital can accelerate the transition from fossil fuels while benefiting both sectors' goals of net-zero carbon emissions strived for by nation-states and the high potential for return on investment craved by investment firms, philanthropists, and private industry. Partnerships provide an acceptable framework for risk and cost-sharing between the public and private sectors. This makes clean energy projects increasingly financially viable and attractive to investors. Collaborations can access innovation funding mechanisms like green bonds, carbon contracts, and climate investment platforms to mobilize capital toward shared goals. [H]
Partnerships facilitate knowledge sharing between academia, industry, and governments to foster technological innovation in renewable energy, grid modernization, carbon capture, and storage. The combined expertise and resources allow for accelerated research, development, and deployment of technologies on a commercial scale. The potential of partnerships in the energy sector looks to expedite the planning, development, and operation of large-scale infrastructure projects necessary for a carbon-free energy system like transmission networks, charging stations, and carbon capture facilities. The model enables governments to leverage private sector efficiencies in designing, constructing, and operating complex infrastructure assets and systems.

These potential partnerships provide a platform for coordinated policy, planning, and regulation between the public and private sectors to enable the transition to carbon-free energy, bolstering the potential of return on investments that drive the injection of capital necessary to tackle such a complex problem. Collaborations can pilot innovation policy across jurisdictions with the potential to quicken the implementation of technological advances like carbon pricing, low carbon procurement targets, and renewable portfolio standards into mainstream society.

Other sectors most notably benefited from PPPs in the last fifteen years include the aerospace, healthcare, and nanomedicine industries. The German Aerospace Center and Airbus Defence and Space collaborated on the TerraSAR-X satellite project in 2007, with overwhelming success, as have NASA, SpaceX, and Boeing, by developing new spacecraft and launch systems. [H] The Alliance of Nanotechnology in Cancer partnership advanced innovative nano-platforms for improving drug delivery, diagnostics, and localized treatment approaches that have led to both FDA-approved products and promising new technologies currently progressing clinical trials. [H] In both industry cases, sharing risk, capital investments, and knowledge collaboration in advancements help lead to successful innovation and creative solutions that individual organizations could not achieve independently.

Despite the overwhelming success seen in PPPs across several industries, there are examples where ambitious large-scale projects with unproven technologies face technological challenges and cost overruns. The International Thermonuclear Experimental Reactor (ITER) nuclear fusion project faced significant delays and budget increases without steadfast results for the billions poured into the project by over 35 countries and private industry. [H] Lack of clarity around objectives, roles, and responsibilities can undermine PPPs. The potential for changes in political or economic conditions is a sufficient barrier that can sway private investment ventures away from the carbon-free innovation industry of the future.

Analytical Confidence

The analytical confidence of this estimate is *moderate*. Sources were reliable and tended to corroborate one another. The analyst worked alone and did not use a structured method. Artificial Intelligence facilitated topic visualization, problem scoping, and sourcing reliable information.

Author: COL Luke Clover

Liquid Cooling is Almost Certain to Maximize Data Center Performance by 2035

Executive Summary

Liquid cooling is almost certain to maximize data center performance by 2035 due to increased efficiency in heat transfer and energy, higher-density computing, and significant cost savings. Traditional air cooling is no longer sufficient to meet the demands of modern computing. Despite the need for increased water supply and sources, liquid cooling allows data centers to achieve the processing power to meet the needs of future information processing, artificial intelligence, and advanced analytics.

Discussion

Data centers use liquid cooling to facilitate improved heat transfer and energy efficiency. Liquid cooling, which utilizes water as its primary coolant, provides a thermal conductivity that is 23 times greater than air, allowing water to absorb and transfer heat from electronic components.[HH] This technology possesses superior heat transfer capabilities allowing for more efficient cooling of high-density racks, resulting in improved energy efficiency in both IT and facility systems when compared to traditional air cooling method.[H] By directly cooling data components with water, this eliminates the need for energy-intensive components like server fans and chillers, significantly reducing overall energy consumption. Liquid cooling also allows for higher chilled water temperatures, optimizing facility infrastructure efficiency, and creating opportunities for waste heat reuse.[H] The use of liquid cooling not only enhances heat dissipation and precision temperature control but contributes to a substantial reduction in total power consumption.

Emerging technologies using AI and machine learning require a powerful infrastructure and rack power densities capable of maximizing their computationally intensive value. Liquid cooling is a technology that enables data centers to support high rack power densities that surpass the capabilities of traditional air cooling.[H] A decade ago, the average data center rack used only 2-5 kW. However, the average has increased to 8.2 kW per rack in 2020, with 29 percent of data centers reporting average densities of 10 kW or higher.[H] Traditional air cooling becomes ineffective beyond 10-15 kW per rack.[H] Predictions indicate that rack power densities of 15-20 kW will become the norm by 2025. Experts anticipate future average rack power densities of 30-50 kW, with some setups reaching up to 100 kW per rack.[H] The demand for compute-intensive workloads is increasing with AI, machine learning, and high-performance computing. Liquid cooling is a crucial enabling technology that allows data centers to support these extreme power densities to meet future data requirements.

Liquid cooling reduces heating energy consumption and carbon emissions allowing for significant cost savings. Astute Analytica reported that future data centers are expected to consume 20 percent of the global power supply by 2025.[H] Traditional cooling costs account for 45 percent of a data center's operating costs. [H] However, the liquid-cooled Barcelona

Supercomputing Center saw a 40 percent reduction in power consumption. [H] Another significant case is the liquid-cooled NSA's Data Center EcoPod which reduced energy usage by 98 percent and water consumption by 50 percent.[H] One data center used an immersion-based system for 48 servers and found the lack of component-generated heat allowed for seven years without routine or emergency maintenance.[H] Liquid cooling has shown the ability for organizations to reduce operating expenses through cost savings in power usage and maintenance requirements.

Data centers use a considerable amount of water and face increasing criticism that they contribute to the mass water shortage in regions suffering from droughts and climate change. Data centers can use up to 5 million gallons of water daily, which is equivalent to a city with 50,000 people.[H] A Virginia Tech study reported that data centers are among the top 10 water-consuming industries in the US, using approximately 513 million cubic meters in 2018.[H] In addition, tech companies constructed many of their data centers in areas where power is cheaper and low-carbon, but water resources are scarce. For instance, California has 239 data centers, while Arizona has 49.[H] However, the tech industry is exploring alternative water sources like wastewater or seawater, reducing reliance on potable water sources. Moreover, the higher thermal conductivity of liquid coolants allows organizations to reuse the cooling water, reducing the overall required water consumption.[H] Liquid cooling demonstrates a more sustainable cooling solution than traditional air cooling methods, especially in regions with drought or water source challenges.

Analytical Confidence

The analytic confidence for this estimate is high. The analyst was not time-constrained and did not use a structured method to develop the report. The analyst did not collaborate on this estimate; however, the estimate falls within the range of reasonable opinion. Sources were reliable and corroborated one another. The time horizon for this analysis is lengthy, and the report is sensitive to change due to new information.

Author: COL Erik Oksenvaag

Advancements in Propulsion Likely to Provide a Path Towards Electrification of the US Army's Maritime Capabilities

Executive Summary

Ongoing developments and adoption of electrified marine propulsion systems within the US Navy and maritime industry should result in a paradigm shift in Army watercraft development with an eye towards energy independence and increased mission endurance. The Army operates numerous landing craft, tugs, barges, dredges, and logistic support vessels with the potential to benefit from a reduced hydrocarbon requirement. [H] Seemingly perpetual theater requirements continue to mandate a sustained sealift capability despite resourcing shortfalls. Operating costs remain a concern as observed with the Maneuver Support Vessel (Light) MSV-L. [H] However, probable advancements in key sectors of maritime capabilities discussed below could potentially result in an Army path towards electrification of its naval assets by 2035.

Discussion

The US Navy recently employed the Saildrone Explorer Unmanned Service Vessel (USV) as part of a series of experiments associated with its newly established Task Force 59 to test advancements in unmanned systems and artificial intelligence (AI). [H] This new, lightweight platform resembles a small sailboat's visual profile utilizing their proprietary "Saildrone wing" for primary motion and a 4kw electric motor for secondary. [H] Onboard power is provided by several affixed solar arrays with a 3+ month endurance at sea with an average 5-knot speed capability. [H] The Navy has experienced significant success with the platform with an operational deployment to the CENTCOM AOR – with threat interest by the Iranian Revolutionary Guard Corps Navy (IRGCN). [H] Though limited in scale at present, the future implication for the Army is the fusion of wind and solar technologies to propel forthcoming iterations of utility vessels. The DoD remains the world's largest consumer of fossil fuels and is dependent on a vast, but at-risk global supply chain to supply it. [H] The development of more capable naval propulsion capabilities based on wind and solar energy as observed with Saildrone should serve as a progressive step forward in the overall electrification of the service.

"Saildrone wing" combines wind and solar panels for propulsion.

Increased mission endurance has long been a requirement for US naval capabilities leading to the advent of nuclear-powered aircraft carriers and submarines. For a limited time, the service also employed nuclear cruisers, but these were later abandoned based on complexity and significant operating costs. Of historical interest and future applicability to the Army was the development and launching of the Nuclear Ship (NS) Savanah on July 21, 1959. The vessel was initially designed as a demonstration project but also served as a functional merchant ship powered by 74 mega-watt Babcock & Wilcox nuclear reactor powering two steam turbines with a cargo capacity of 14,000 tons. [H] Most noteworthy however was its maximum speed of 24 knots with a range of over 350,000 miles per load of fissile fuel. During its service life, the vessel traveled over 450,000 nautical miles until it was deactivated in 1971 based on excessive operating costs determined at the time. [M] Since then, ongoing advancements in nuclear technology have rendered improved power generation with the ongoing construction of Ford-class carriers with Bechtel A1B 125 megawatt reactors. It is feasible that the Army could consider the development of nuclear-powered cargo vessels able to transport large amounts of vehicles, troops, and material with extended mission endurance at sea with reduced requirements for fueling and logistics support. Such an endeavor would require careful fiscal management to avoid acquisition oversights currently being reported with the MSV-L which has doubled per unit cost from $27.8 million to $63.1 million. [M] Nuclear-capable platforms should be carefully managed to sustain tax-payer confidence in their enduring use.


NS Savanah is the only nuclear-powered merchant vessel ever built.

Analytical Confidence

The analytic confidence of this estimate is *moderate* based on published technical developments within the industrial base and current reporting of applications in the CENTCOM AOR. There appears to be insufficient guidance and incentive for the Army to explore the electrification of its obscure maritime capability.

Author: LTC Eric Soler

eVTOL a Likely Roadmap Towards Electrification of Army Aviation

Executive Summary

The electric vertical takeoff and landing vehicle (eVTOL) is a likely path toward decarbonizing vertical lift aviation based on advancements in motor drive technology, the potential for reduced maintenance costs, and inherent stealth capabilities. Despite contemporary rotorcrafts' longevity of demonstrated performance and industrial support, eVTOLs at reduced scale have emerged as viable reconnaissance and weapons platforms in the current Russo-Ukrainian War. H Over 200 global companies have invested significant resources to advance eVTOLs for increased range and capacity. H It is likely feasible that by 2035, this capability will achieve the technical maturity required for combat platform development.

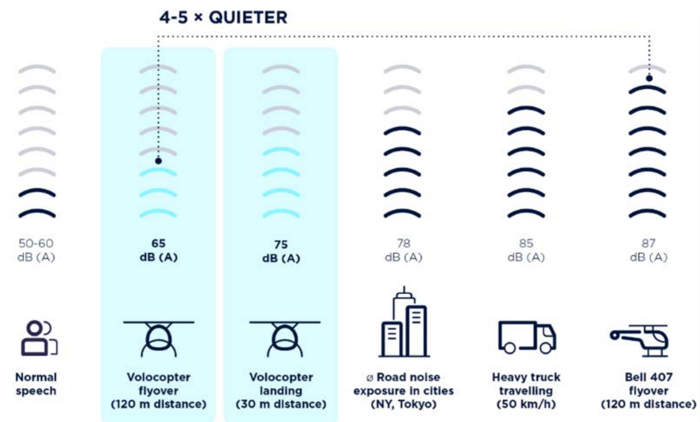
Discussion

Conceptualization of Archer Midnight operating on a US Aircraft

The overall engineering concept behind eVTOL is the electrification of specialized motors combined with propellers to achieve lift. While the technical details of power generation and propulsion remain sophisticated and the subject of ongoing advancement, specialists within the field advocate for the platform's advantages against traditional helicopters. Airframes such as the UH-60 Blackhawk or AH-64 Apache employ complex turboshaft engines that rely upon a tail rotor to stabilize flight. These systems contain multiple single points of failure that require significant maintenance and associated costs. H Prevailing eVTOL designs such as Archer's production Midnight aircraft mount twelve independent prop motors that provide substantial redundancy should one or more fail. This technology could feasibly reverse current Army flight readiness trends, which for the last 10 years failed to meet statutory requirements, including the airframes mentioned above. H

The production of a military electric aircraft with a capability like a UH-60 or AH-64 platform would incur significant research and development costs. Current civilian production-ready models face steep upstart costs and financing required for ongoing FAA testing and certification. However, advocates for eVTOL cite foreseeable cost savings for the airframe in maintenance and training. The overall simplicity of electric aircraft design—specifically the reduction of mechanical articulation— decreases potential failure and the logistics chain required to support it. The specialized training needed to attend to complex gas turbine engines is lowered thus further diminishing uniformed personnel requirements and contractor support. Flying eVTOLs has been reported to be less complicated than traditional helicopters, further minimizing the required cost.

The inherent tactical advantage of eVTOLs is the reduction of noise emissions compared to conventional helicopters. By contrast, military helicopters, characterized by their massive jet engines and propellers rotating at over 500 revs per minute emit easily detectable noise signatures. This lack of stealth capability compromises their tactical effectiveness, leaving them vulnerable to enemy detection and attack, as evidenced by past incidents such as the destruction of a modified UH-60 during the clandestine operation targeting Osama Bin Laden in Pakistan. H



Significant reduction in noise emissions with eVTOL platform

Analytical Confidence

The analytic confidence of this estimate is *moderate* based on good quality technical and financial sourcing that can be researched online regarding eVTOLs. H Published data on performance parameters and progress towards flight certifications is also well detailed. H There is a dearth of information however on actual DoD activities on the technology outside of small-scale platforms such as drones or other Unmanned Aerial Vehicles (UAS).

Author: LTC Eric Soler

Hybrids Likely for the U.S. Army's Tracked Vehicles Beyond 2035

Executive Summary

The hybridization of the Army's tracked vehicles provides a likely path toward electrification beyond 2035 due to supporting infrastructure, potential performance advantages, and the lack of current electrification capabilities. Despite the infeasibility of absolute electrification for these platforms, ongoing advancements in hybridized drivetrains are likely to provide a viable bridging strategy until technology shortfalls are resolved for future development.

Discussion

To achieve decisive superiority on land, the Army employs tracked combat vehicles developed to operate in austere environments and endure battle damage while leveraging superior firepower. Uncontested logistics support – specifically, the Army's ability to resource and distribute fuel in forward operating locations has provided seemingly untethered mobility for our heavy maneuver forces. However, strategic projections have raised concerns about the vulnerabilities of sustainment infrastructure and supply chains to future adversaries. [H] The Army-tracked inventory requires considerable quantities of petroleum-based fuels to sustain gas turbine and diesel engines. [H] This threat could be mitigated with electrified tracked variants, yet the technical application of current energy and propulsion systems impedes the overall concept. These vehicles remain encumbered with high-weight requirements that adversely impact their electrified endurance potential. [H]

The Abrams X Technology Demonstrator Prototype

The 2022 Army Climate Strategy's exemption of tanks from its objective milestones raises questions about the extent of the military's commitment to electrification. [H] Despite this exemption, there's notable progress in exploring electrification within the military and its industry partners. For instance, General Dynamics Land Systems (GDLS) has introduced the Abrams X, representing a significant step towards hybrid technology. This technology demonstration combines a hybrid Cummins diesel engine with an electric power pack, operating simultaneously. [M] Incorporating this hybrid system can yield several advantages, such as enabling a "silent watch" capability during idle periods or low power mode, extending the tank's operational range, and providing an exportable power option. The introduction of this hybrid system not only represents a technological advancement but also hints at a potential shift in the evolution of US tanks. Notably, the simplified hybrid system could lead to a significant weight reduction, potentially up to 10 tons, which could mark a departure from the traditional heavier gas turbine engines. This weight reduction not only enhances the tank's maneuverability and efficiency but also paves the way for future full electrification efforts. Therefore, while the exemption of tanks from the climate strategy may suggest a slower pace in electrification, initiatives like the Abrams X demonstrate a promising path forward, showcasing how hybrid technologies can offer immediate benefits while laying the groundwork for broader electrification in the future. [M]

Other tracked vehicles not designated as tanks, such as future variants of the BFV, M10, and XM30 will be subject to the 2022 mandate of fielding purpose-built hybrid-drive tactical vehicles by 2035 and fully electric tactical vehicles by 2050. H The M10 Booker is currently undergoing low-rate production and operational testing with fielding scheduled for 2025. At present, the platform does not employ significant components of an electrified drive train. As the planned successor to the BFV, the XM30 is undergoing prototyping between two vendors with the requirement for a hybrid electric powertrain. H

Bradley Fighting Vehicle undergoing hybridization retrofit

The Rapid Capabilities and Critical Technologies Office (RCCTO) recently unveiled a notable development towards electrification in 2022 with its Bradley Hybrid Electric Vehicle (BHEV). Building upon this 40+ year platform, BAE was able to retrofit two test vehicles with upgraded diesel engines, replacing the transmission with QinetiQ electric cross-drive transmission (Modular E-X-Drive) motors, and installing lithium-ion batteries. M The assessment of these prototypes concluded in the 4th quarter of FY22, although the results remain unclear, as does the direction the Army intends to embark upon. A study by SAE International, published in 2023, demonstrates the feasibility of fully electric and hydrogen-powered Bradley variants using off-the-shelf technology. M The analysis employed software modeling to assess the potential of these variants. The electrified variant was modeled with a 140.25 kWh battery pack, adapted from the A123 Systems ANR26650m1-B utilized in Tesla Extended Range vehicles, adjusted for the application. M Similarly, the hydrogen-powered Bradley was hypothetically equipped with a scaled version, increased by a factor of 30, of a 1.24 kWh power pack found in the Toyota Mirai. The study reveals various performance outcomes influenced by environmental and operational factors. Additionally, it underscored the importance of trained expertise and infrastructure requirements necessary to implement either power source effectively. M

An Institute for Energy Research (IER) June 2023 commentary summarizes the current state of electrification with, “Currently, the technology does not exist to generate, store, and distribute electric power in a tactically relevant amount of time for frontline troops to be equipped with all-electric weapons and support vehicles”. H The article indicates the charging capacity needed to reenergize a 50-ton combat vehicle in the field within 15 minutes would require a 17-megawatt mobile charging station that is 20 times bigger than anything the Army currently operates. H They also caution against becoming dependent on battery technology as China controls 80 percent of the global supply chain rendering the US four times more dependent on it than our Middle Eastern sources for oil. H

Analytical Confidence

The analytic confidence of this estimate is *high* based on contemporary assessments of battery technology and the lack of performance data on the BHEV; the US Army has not publicized a decision. Available material for the electrification of tracked vehicles remains limited.

Author: LTC Eric Soler

Annexes

Annex A: Terms of Reference

Terms of Reference:

Conditions Setting for Electrification of the U.S. Army

For:

HON Rachel Jacobson
Assistant Secretary of the United States Army
Installations, Energy and Environment (ASA IE&E)

By:

Team ATROPOS
U.S. Army War College
Futures Seminar

December 5, 2023

Terms of Reference:
Conditions Setting for Electrification of the U.S. Army

Requirement:

What capabilities[5] are likely to become available between now and 2035 to support the transition of the U.S. Army from a carbon-based energy-reliant organization to an electrified, carbon-free force?

- What viable options are likely to emerge that the Army can invest in to reduce the demand for carbon-based fuels that are now used for power installations and contingency-basing?
- What emerging technologies will likely be available to provide the adequate carbon-free power needed for the tactical vehicles of the future?
- What global infrastructure innovations will be available by 2035 that may impact installation and contingency bases?
- What emerging energy options could preserve and enhance capabilities for the operational Army?
- What obstacles might hinder the implementation of the electrification of the force by 2035?

Methodology:

The team intends to research and gather information through various means, including but not limited to open-source outlets, current Army doctrinal references, and interviews with subject matter experts from across the US government, industry, public sector, academia, and research institutes. Further, we will request data from tech hubs focused on green energy and sustainability and gather data from public and private sector electrification projects for municipal and contingency energy requirements.

The team expects to execute this project in the following four steps (Note: This is a notional timeline only. The team will remain flexible to take advantage of opportunities and to address unforeseen limitations):

Step 1: Modeling and Data Collection (November 2023 to January 2024)

- Evaluate the current state of decarbonization methods inside and outside of the Army.
- Evaluate current decarbonization plans in other government organizations.
- Collect information on emerging technologies.
- Collect information from subject matter experts on future decarbonization methods.

Step 2: Analysis (January 2024-March 2024)

- Analyze feasibility and suitability of decarbonization capabilities.

[5] Capabilities refers to both products and processes.

- Determine obstacles to decarbonization capabilities (supply chain, technology maturation, et cetera)
- Determine implementation gateways for decarbonization capabilities as required for the U.S. Army.
- Model decarbonization capabilities for 2035.

Step 3: Communication Preparation (March 2024)

- Conduct a peer review of findings.
- Revalidate assumptions, finalize analysis, and finalize briefing media.

Step 4: Out-brief to HON Jacobson and team (April 2024-May 2024)

- Prepare four hard copy briefing books and accompanying digital files compiling the team's final report
- Provide executive out brief via teams, utilizing PowerPoint or other applicable media

Challenges:

- The research team's concurrent coursework for the Army War College curriculum limits opportunities for detailed research via in-person TDY.
- Some experts may hesitate to share proprietary knowledge/information due to corporate competition and/or internal restrictions.

Resources:

- The team will make full use of the technology, links, and networks provided by the AWC Futures Seminar.
- Team members have connections within the DoD and private sector along with diverse backgrounds, including expertise in resource management, Army installation oversight, formal research processes, and using data analytics to synthesize data.
- AI and advanced modeling tools are available to assist in scenario development.
- Several technology hubs, such as the South Carolina Nexus for Advanced Resilient Energy, are on the East Coast, providing opportunities for a greater understanding of emerging technologies.

Administration:

- The team will provide their Futures Seminar instructors with both a PDF and digital version a final draft product for review.
- Secretary Jacobson, her staff, and Futures Seminar instructors will receive a Read Ahead (RAH) before the final briefing occurs.
- The team is comprised of the following students with their emails and phone contacts:

Team Point of Contact
Eric Y. Soler
eric.y.soler.mil@armywarcollege.edu
915-218-9702

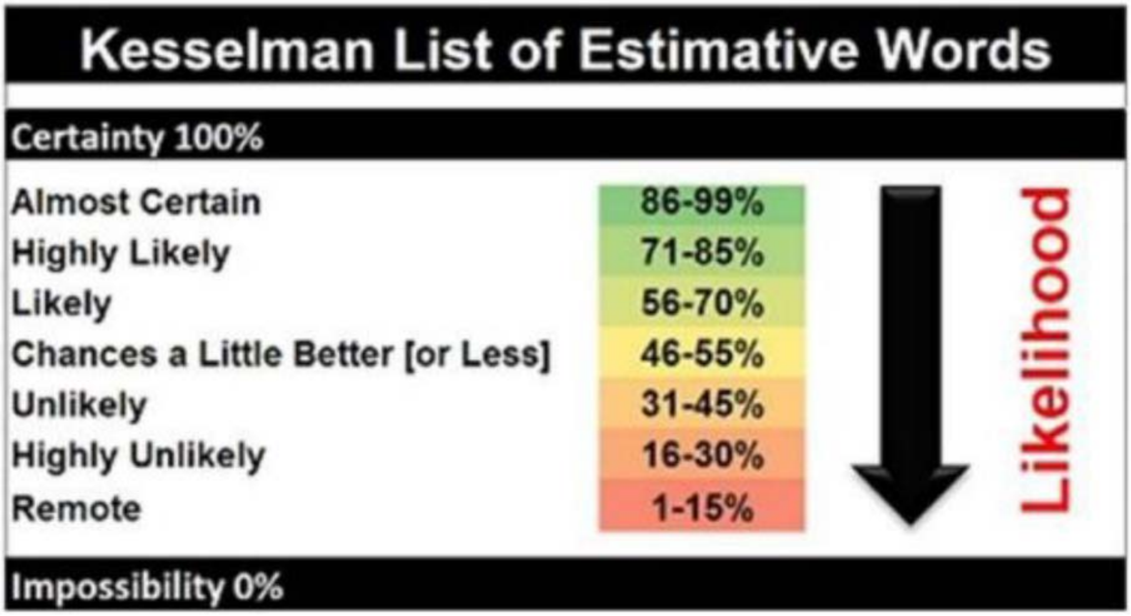
Alternate Team Point of Contact
Stacy L. Moore
stacy.l.moore32.mil@armywarcollege.edu
931-809-0714

Team Members
John M. Oliver
john.m.oliver32.mil@armywarcollege.edu
910-495-3459

Erik C. Oksenvaag
erik.c.oksenvaag.mil@armywarcollege.edu
310-529-7124

Luke R. Clover
luke.r.clover.mil@armywarcollege.edu
925-623-2504

Annex B: Words of Estimated Probability



Kesselman List of Estimative Words

Certainty 100%	
Almost Certain	86-99%
Highly Likely	71-85%
Likely	56-70%
Chances a Little Better [or Less]	46-55%
Unlikely	31-45%
Highly Unlikely	16-30%
Remote	1-15%
Impossibility 0%	

Annex C: Standard Primary Source Trust Scale

Standard Primary Source Credibility Scale

Source reliability is noted at the end of each citation as low L, moderate M, or high H. The citation is hyperlinked to the source, unless the source is a paid subscription; in that instance a footnote is provided at the end of each writing illustrating the source for credibility. Source reliability is determined using the Trust Scale and Website Evaluation Worksheet found in Annex

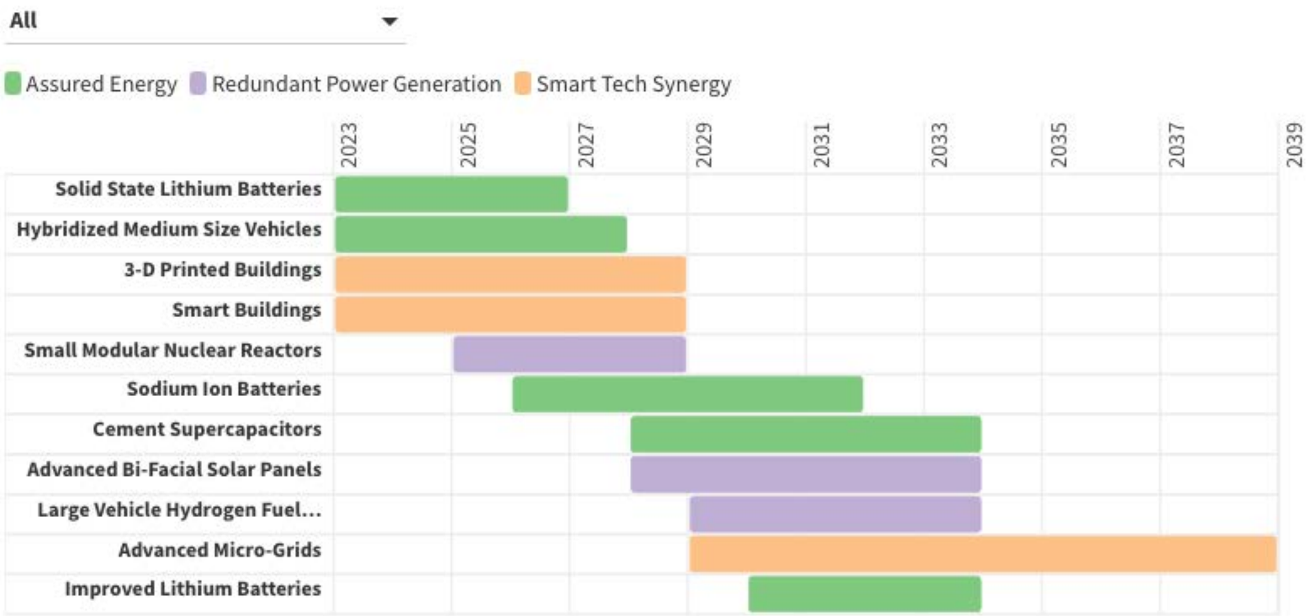
Importance	Factor	Description	Satisfies Criteria (Yes /No)
HIGH	Has a good track record	Source has consistently provided true and correct information in the past	
	Information can be corroborated with other sources	Information provided by the source corroborates with information from other primary and/or secondary sources	
	Information provided is plausible	High probability of the information being true based on the analyst's experience of the topic/subject being investigated	
	Information is consistent and logically sound	Information provided is consistent when queried from different angles and is logically sound	
	Perceived expertise on the subject	Source is perceived to be an expert on the subject / topic being investigated and/or is in a role where subject knowledge is likely to be high	
	Proximity to the information	Source is close to the information – a direct participant or a witness to the event being investigated	
	Perceived trustworthiness	Source is perceived to be truthful and having integrity	
MEDIUM	No perceived bias or vested interest in the subject / topic being investigated or on the outcome of the research	Source has no perceived bias or vested interest in the subject / topic being investigated or on the outcome of the research	
	Provides complete, specific and detailed information	Information provided is specific, detailed and not generic	
LOW	Is articulate, coherent and has a positive body language	Source is articulate, coherent, has a positive body language and does not display nervousness or body language that can be construed to be evocative of deceptive behavior	
	Recommended by another trusted / credible third party	Source is recommended by others the analyst trusts but the analyst herself does not have any direct experience working with the source	
	Sociable	Source comes across as outgoing and friendly. Easy to get along with and talk to	
	Perceived goodwill to the receiver	Perceived intent or desire to help the receiver or the analyst	

Annex D: Peterson's Analytic Confidence Worksheet

Peterson's Analytic Confidence Worksheet

	Points Possible	Points
Use of Structured Method(s) In Analysis	(1-10)	
For example: ACH, IPB, Social Networking, Bayes, Simulation, etc…		
10 indicating highest possible score when considering factors below		
Consider		
Number of		
Applicability of methods to the analysis		
Level of robustness of method		
Degree to which methods' results coincide		
Overall Source Reliability	(1-10)	
A rating of 10 indicates the highest reliability		
Source Corroboration/Agreement: *Level of conflict amongst sources*	(1-5)	
5: No confliction amongst sources		
4: Very little conflict amongst sources		
3: Moderate conflict amongst sources		
2: Significant conflict amongst sources		
1: Sources conflict on nearly all points		
Level of Expertise on Subject/Topic & Experience	(1-5)	
5: Deep intimate knowledge and understanding & 3+ years experience with topic		
4: Wide knowledge & 1-3 years experience with topic		
3: Moderate knowledge & 6-12 months experience with topic		
2: Minimal knowledge & 0-5 months experience with topic		
1: No knowledge & no experience with the topic		
Amount of Collaboration:	(1-5)	
5: Part of aggregated individual analyses		
4: Work on a team		
3: Worked with a partner		
2: Casual discussion		
1: Completely individual work		
Task Complexity	(1-5)	
5: Minimally complex & challenging		
4: Somewhat complex & challenging		
3: Moderately complex & challenging		
2: Quite complex & challenging		
1: Very complex & high challenging		
Time Pressure: *Time given to make analysis*	(1-5)	
5: No deadline		
4: Easy to meet deadline		
3: Moderate deadline		
2: Demanding deadline		
1: Grossly inadequate deadline		
	Score:	
	Total Possible:	**45**
	Score/Total Poss:	
		X10
	Analytic Confidence Adjusted Score:	

Annex E: Technology Gantt Chart



Annex F: Policy Resistance Data

State	State-Level Restrictions	Local Restrictions	Contested Projects
Alabama	0	4	3
Alaska	0	0	0
Arizona	0	0	0
Arkansas	0	0	1
California*	0	3	14
Colorado	0	1	4
Connecticut*	1	0	2
Delaware	0	2	3
Florida*	0	0	2
Georgia	0	5	1
Hawaii	0	0	1
Idaho	0	2	3
Illinois*	0	5	11
Indiana	0	21	12
Iowa*	0	10	10
Kansas	1	9	7
Kentucky	1	0	4
Louisiana	0	2	1
Maine	1	9	10
Maryland*	0	5	4
Massachusetts*	0	2	12
Michigan	0	26	15
Minnesota*	1	2	4
Mississippi	0	0	0
Missouri	0	4	3
Montana	0	0	4
Nebraska	0	18	5
Nevada	0	0	10
New Hampshire	0	0	4
New Jersey*	0	2	3
New Mexico*	0	0	5
New York*	1	21	27
North Carolina	0	9	4
North Dakota	0	4	6
Ohio	1	13	15
Oklahoma	0	2	2
Oregon	1	1	8
Pennsylvania	0	1	5
Rhode Island*	0	3	9

South Carolina	0	0	2
South Dakota	0	4	4
Tennessee	0	2	0
Texas	0	14	5
Utah	0	1	0
Vermont*	0	0	8
Virginia	0	10	12
Washington*	0	4	6
West Virgnia	0	0	2
Wisconsin*	0	6	5
Wyoming	0	1	2

***State law allows for the state to supercede local laws**

Data tabulated from a 2023 report from Columbia University Law School.[H]

Annex G: Expert Interview Notes

Meeting Minutes with Dr. Peter Schil - Senior Research Scientist (ST)
Ground Vehicle Propulsion and Mobility
US Army Combat Capabilities Development Center (DEVCOM)
Conducted on THUR, 4 APR 24 at 0900 EST

Executive Summary

Dr. Peter Schihl delivered an insightful overview of the ongoing initiatives to electrify current and future ground combat systems within the US Army, tracing back two decades of efforts. He identified energy density as the primary technical hurdle hindering the widespread adoption of electrification in ground vehicles. Despite advancements in lithium-ion battery technology, current capabilities fall short of meeting the performance demands of wheeled and tracked platforms compared to traditional carbon fuel-based powertrains. Dr. Schihl advocates for an incremental approach, focusing on achievable objectives such as electrifying light-wheeled vehicles, implementing hybridization, and reducing onboard energy consumption for auxiliary equipment until battery technology matures further.

Discussion

LTC Soler started the meeting with an introduction to the Futures research group members. Dr. Schihl conveyed his appreciation for the team's commitment and enthusiasm toward advancing the project's objectives. Delving into some historical context, he provided a sweeping narrative detailing two decades of concerted efforts in electrification, spurred by mandates emanating from various quarters including the military hierarchy and successive presidential administrations, all with the overarching aim of decarbonization. Despite these concerted endeavors, the formidable challenge of energy density continues to thwart progress. Dr. Schihl underscored the prevailing inadequacy of current lithium-ion battery technology to meet the exacting performance standards demanded by combat vehicles in operational settings.

Additionally, Dr. Schihl shed light on the conspicuous absence of logistical infrastructure requisite for supporting the generation, distribution, and storage of high-voltage power. The discourse then transitioned to ongoing initiatives aimed at electrifying extant vehicular platforms. Here, Dr. Schihl reiterated the promise held by certain technological advancements, albeit none reaching the threshold for production. Illustrating his point with the paradigm of a Main Battle Tank encumbered with substantial weight while still expected to maintain peak combat lethality, Dr. Schihl emphasized the nation's and the Army's reluctance to compromise on performance in the pursuit of decarbonization.

When pressed for his insights regarding the requisite capabilities to facilitate decarbonization within a timeline extended to 2025, Dr. Schihl delineated three pivotal considerations. Firstly, he advocated for judicious investment in the electrification of lighter tactical and commercial utility vehicles, alongside the essential infrastructure necessary for their sustainment, underlining the imperative of meticulous execution. Secondly, he opined that the decarbonization of medium and heavy vehicle variants remains a formidable challenge, thus propounding the adoption of hybrid diesel/electric drivetrains as an interim measure until battery technology attains maturity. This recommendation was complemented by his highlight for instilling a culture of energy discipline within the organization.

Lastly, Dr. Schihl stressed the imperative of devising strategies to mitigate the escalating energy consumption emanating from onboard ancillary equipment, propelled by the continual advancements in sensors, communications, and weapon systems. The gathering concluded with Dr. Schihl extending his gratitude to the assembled group and offering to provide any further assistance required to advance our collective research endeavor.

Meeting Minutes with Mr. Gregoy Slawson – Chief Strategy Officer
ZappBatt
Conducted on MON, 8 APR 24 at 1300 EST

Executive Summary

Mr. Gregory Slawson provided a comprehensive overview of ZappBatt's work towards enabling electrification by advancing lithium-ion technologies and incorporating innovative operating systems. Their vision is to increase the energy potential of batteries while optimizing performance to improve power conservation and service life. On the matter of capabilities needed to enable the decarbonization of the US Army by 2025, Mr. Slawson recommended increased Department of the Army (DoA) requirements for electrified platforms as well as optimization of systems to maximize power efficiency.

Discussion

LTC Oliver initiated the meeting with an introduction to the members of the Futures research team as well as reiterating the given research prompt provided by HON Rachel Jacobson (IE&E). Mr. Slawson then introduced Mr. Daniel Glenn (Chief Operating Officer) and thanked the research group for their interest in the field and service to the nation. Both gentlemen provided a brief overview of their company's portfolio which includes advancing battery hardware and storage capabilities. The firm utilizes Toshiba lithium titanium oxide batteries at the center of their ZappBatt battery pack which employs an intuitive operating software to regulate voltage above expected parameters. They have been able to convert a 12v battery to 25v output sufficient to power small cordless vacuum cleaners. Additionally, their propriety battery operating systems enable upwards of 80% charge within six minutes and increase battery lifespan to 20,000 recharging cycles.

Addressing the matter of capabilities required to enable decarbonization of the Army by 2025, both gentlemen spoke of their understanding and past experiences working with the DoD as well as opportunities and challenges towards its accomplishment. Despite the company's progress toward improving battery technology, Mr. Slawson highlighted the seemingly insurmountable challenge of developing energy density within batteries to propel Army combat platforms within tactical environments. Both gentlemen stressed the need for further DoD investment within the field and to prioritize feasible platforms until energy solutions manifest for larger applications. For larger platforms such as heavy-wheeled and tracked tactical vehicles, both Slawson and Glenn highlighted the lack of financial incentives for civilian companies thus being a potential obstacle towards advancement in the field. They also advocated for improved management of power systems for both mobile and installation applications. Using the example of their software to optimize batteries, both men believe the same concept should be applied to larger power grids, microgrids, and expeditionary power.

The meeting ended with Mr. Slawson and Glenn expressing their support for the project and offering any additional support as required.

Meeting Minutes w/Dr. Mads Almassalkhi and Dr. Amritanshu Pandey Associate Professors of Electrical & Biomedical Engineering
The University of VeConducted on FRI, 12 APR 24 at 0900 EST

Executive Summary

Dr. Almassalkhi and Dr. Amritanshu received an initial draft of key findings before the scheduled engagement. Both provided constructive technical feedback with an overall endorsement of our critical assessments. Sodium-ion batteries were highlighted as an outlier as they believe the technology remains in early development. Key takeaways from the professors regarding decarbonization by 2025 include ongoing investment in battery technology, diversification of energy sources, and cyber security of vulnerable energy systems.

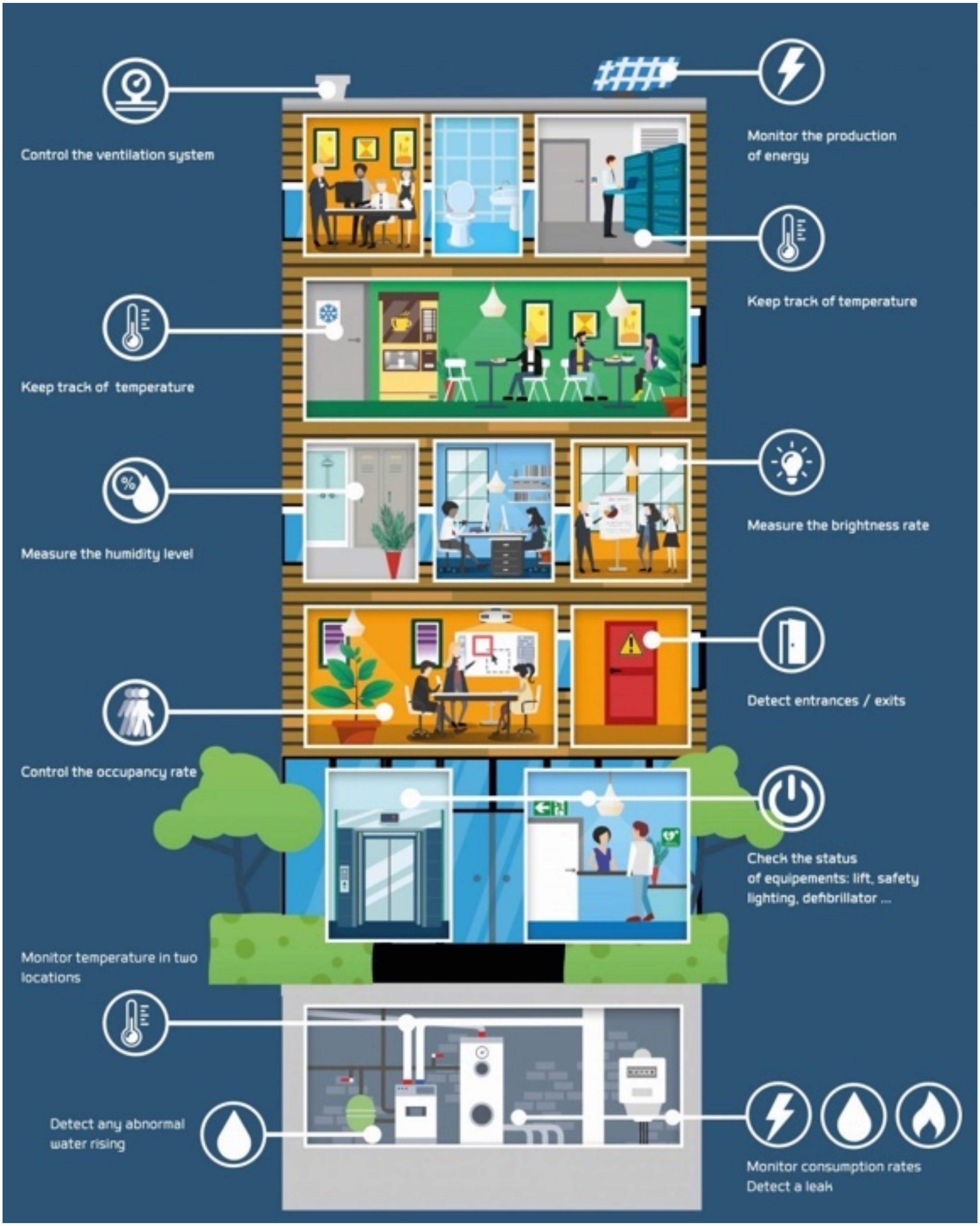
Discussion

The meeting began with a brief introduction from Futures Seminar members and was reciprocated by Dr. Almassalkhi with his background in power systems, mathematical optimization, and renewable energy integration. Dr. Pandey followed with his experience in electric grid optimization, grid cybersecurity, and power grid computations. Both gentlemen had reviewed our key findings and complimented our estimative analysis of requisite capabilities needed for decarbonization. They expressed a varying opinion regarding sodium ion batteries indicating R&D remains ongoing and infrastructure for large-scale production remains limited. Advancements in lithium-ion batteries were discussed, but both Almassalkhi and Pandey expressed the technology may have only limited tactical application for the US Army – specifically with light-wheeled platforms and small scall micro-grids. Hydrogen fuel cells were also highlighted in their energy density and feasibility to power larger utility and tactical vehicles. However, they cited that significant investments in infrastructure to facilitate production, storage, and distribution would be required. Miniaturized nuclear energy was discussed with potential applications to microgrids and large vehicular applications (e.g. submarines). However, Dr. Almassalkhi expressed concern about the lack of nuclear expertise within the US workforce needed to construct and maintain miniature reactors. Wireless transmission of power was also discussed with its applications for forward Army basing and vehicular charging. Dr. Almassalkhi indicated however the capability is limited to 10 inches from node to node.

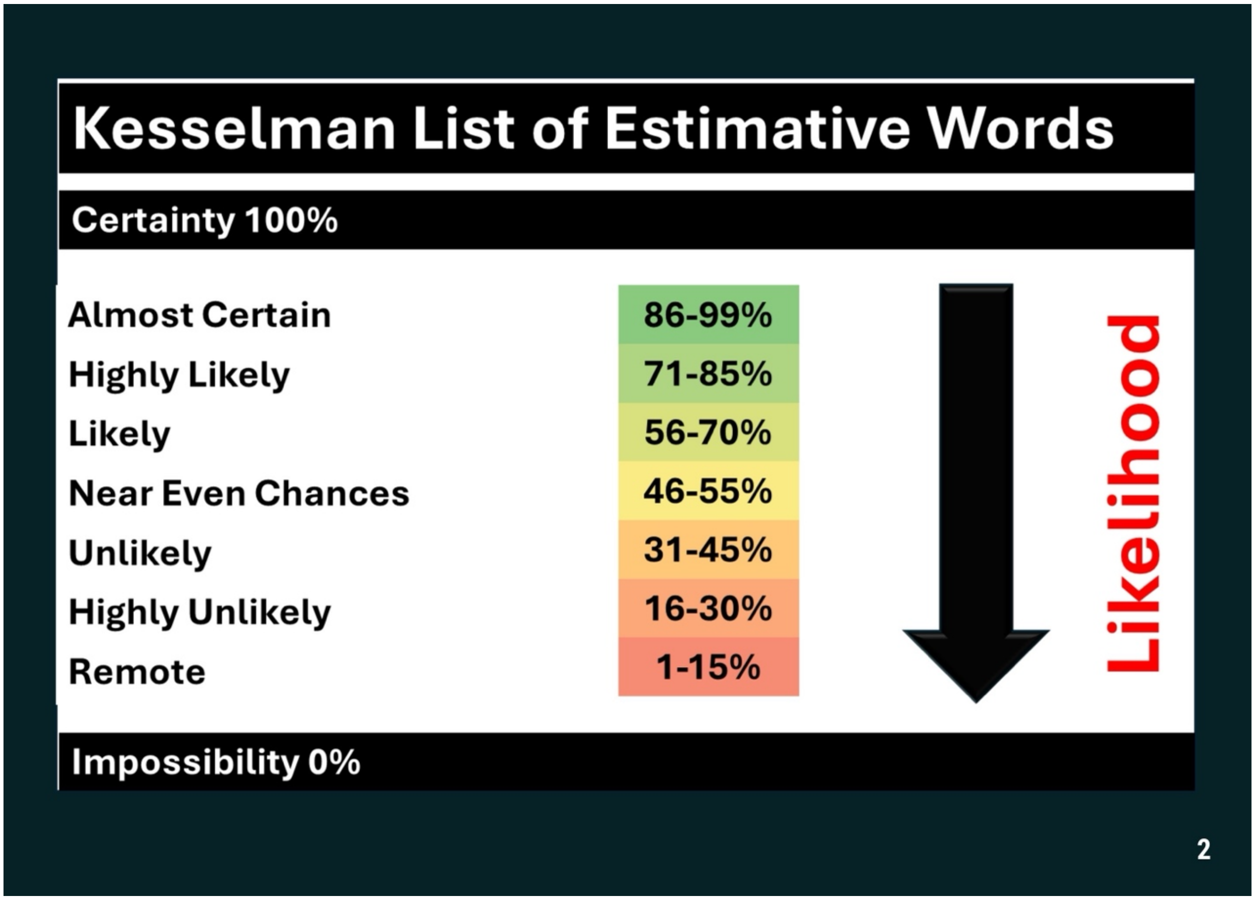
When queried for their perspectives regarding the capabilities needed to enable a decarbonized Army by 2025, both gentlemen proposed the following: 1) Both macro and micrograds should be designed for reliability with redundant power sourcing (e.g. nuclear, wind, solar, hydrogen, geothermal, etc) with innovative optimization to maximize energy efficiency. 2) Energy grids and vehicle-borne electrical systems must be designed to safeguard against cyber threats. Dr. Pandey was adamant in his stipulation as he used the example of today's legacy mechanical control systems that still rely on manual human input. He believes power systems of the future will be predominately managed by software and be subject to increased vulnerability to nefarious activities. The meeting concluded with assurances of future support should our research require.

Dr. Almassalkhi has since provided information on a DOE program called “Energy Shed”.

Annex H: Smart Building Graphic



Annex I: Presentation Slides


Kesselman List of Estimative Words
Certainty 100%
Almost Certain
86-99%
Highly Likely
71-85%
Likely
56-70%
Near Even Chances
46-55%
Unlikely
31-45%
Highly Unlikely
16-30%
Remote
1-15%
Likelihood
Impossibility 0%
2

ANALYTICAL CONFIDENCE

The overall analytic confidence of this estimate is **MODERATE.**

3

RESEARCH QUESTION

What capabilities are likely to become available between now and 2035 to support the transition of the U.S. Army from a carbon-based energy-reliant organization to an electrified, carbon-free force?

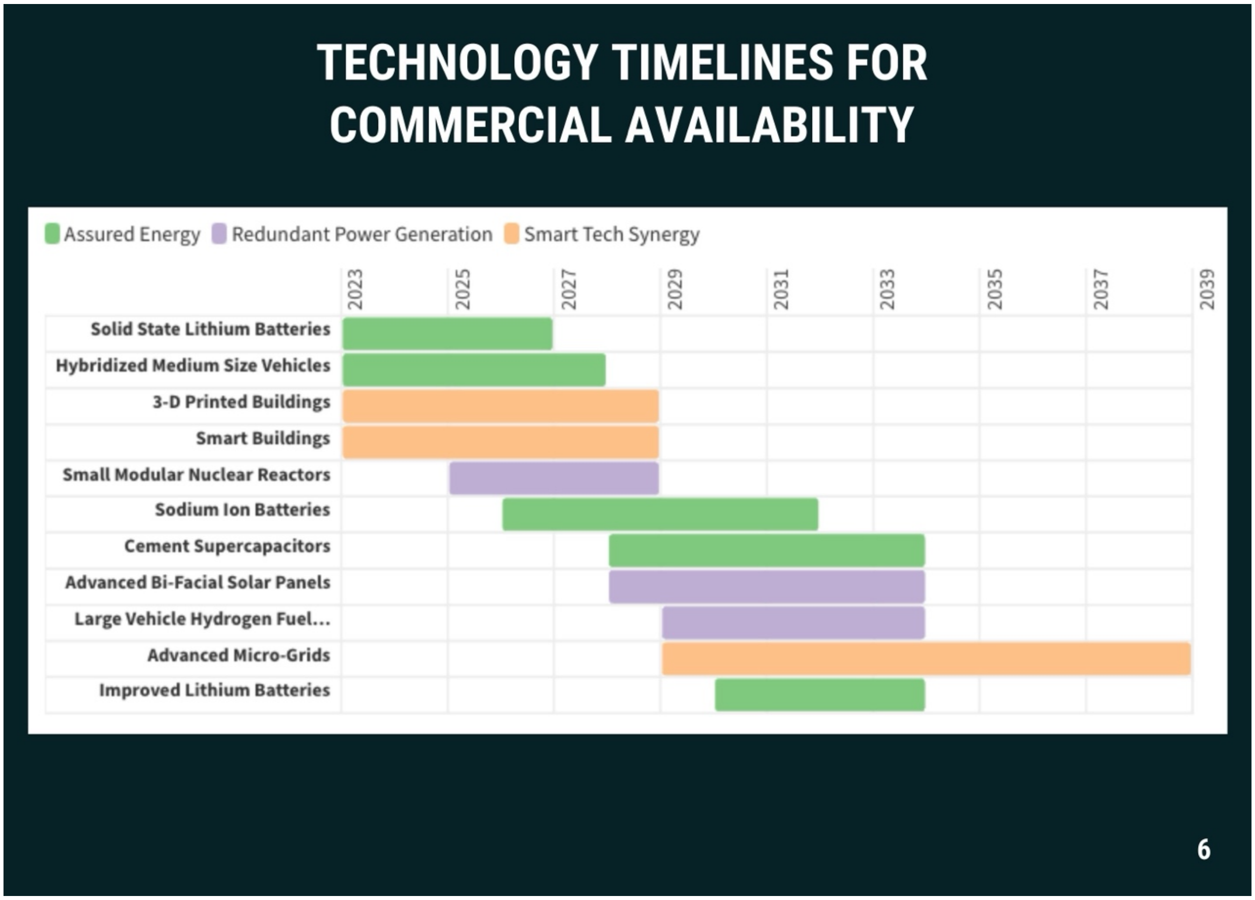
4

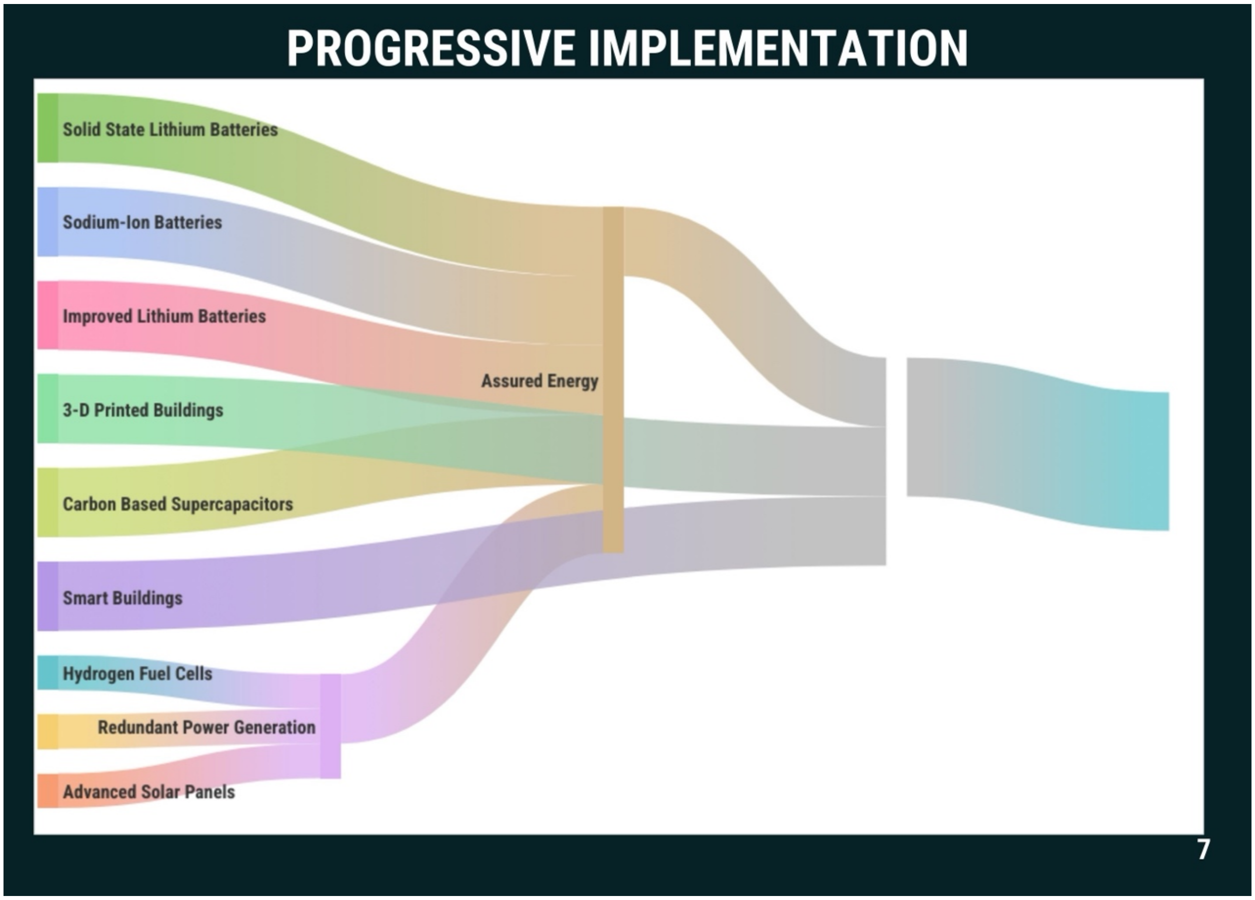
KEY FINDINGS

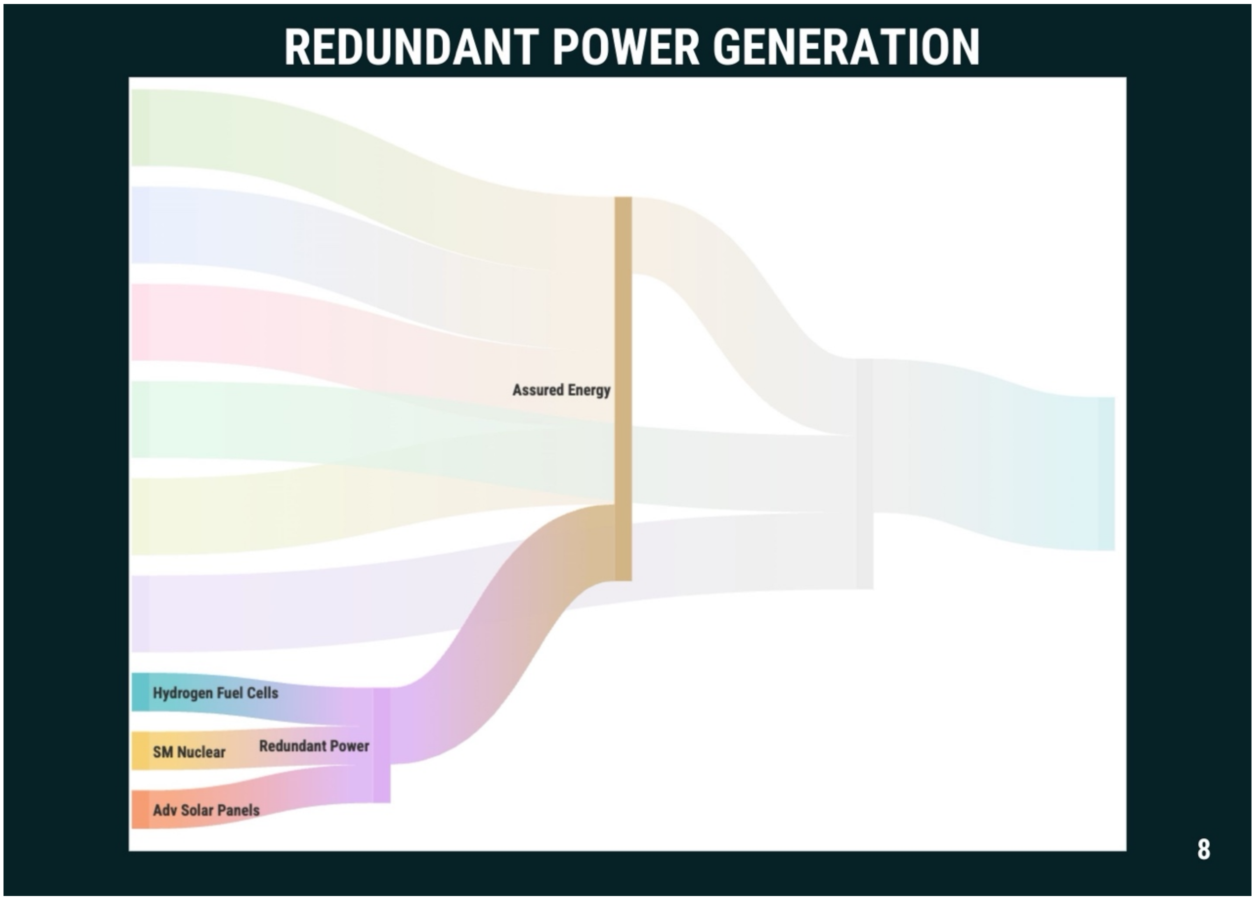
It is highly likely that 11 capabilities in three Emergent Capability Domains will support the Army's transition to decarbonization

Emergent Capability Domains		
Redundant Power Generation	**Assured Energy**	**Smart Tech Synergy**
Small Modular Nuclear Reactors	Solid State Lithium Batteries	3D Printed Buildings
Advanced Bi-Facial Solar Panels	Hybridized Medium Size Vehicles	Smart Buildings
Large Vehicle Hydrogen Fuel Cells	Sodium-Ion Batteries	Advanced Microgrids
	Cement Supercapacitors	
	Improved Lithium-Ion Batteries	

5

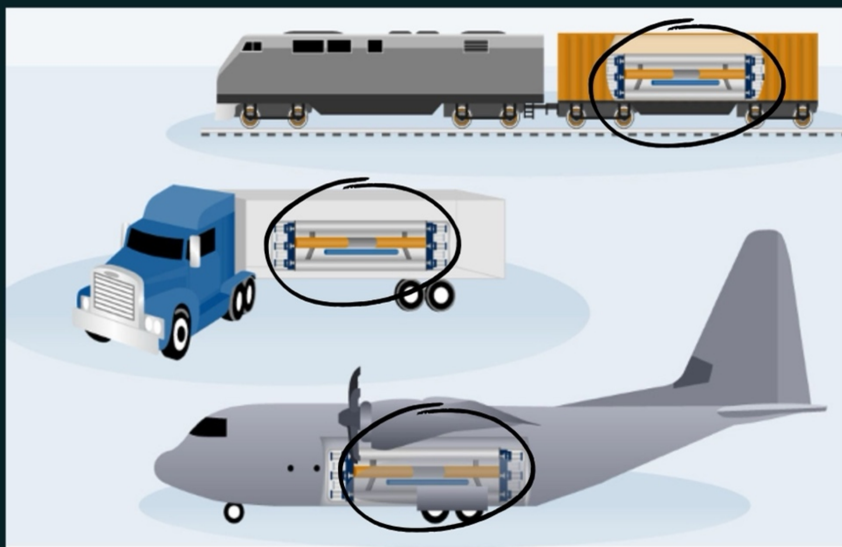

TECHNOLOGY TIMELINES FOR COMMERCIAL AVAILABILITY
Assured Energy
Redundant Power Generation
Smart Tech Synergy
2023
2025
2027
2029
2031
2033
2035
2037
2039
Solid State Lithium Batteries
Hybridized Medium Size Vehicles
3-D Printed Buildings
Smart Buildings
Small Modular Nuclear Reactors
Sodium Ion Batteries
Cement Supercapacitors
Advanced Bi-Facial Solar Panels
Large Vehicle Hydrogen Fuel...
Advanced Micro-Grids
Improved Lithium Batteries
6


PROGRESSIVE IMPLEMENTATION
Solid State Lithium Batteries
Sodium-Ion Batteries
Improved Lithium Batteries
3-D Printed Buildings
Carbon Based Supercapacitors
Smart Buildings
Hydrogen Fuel Cells
Redundant Power Generation
Advanced Solar Panels
Assured Energy
7


REDUNDANT POWER GENERATION
Assured Energy
Hydrogen Fuel Cells
SM Nuclear
Redundant Power
Adv Solar Panels
8

SMALL MODULAR NUCLEAR REACTOR

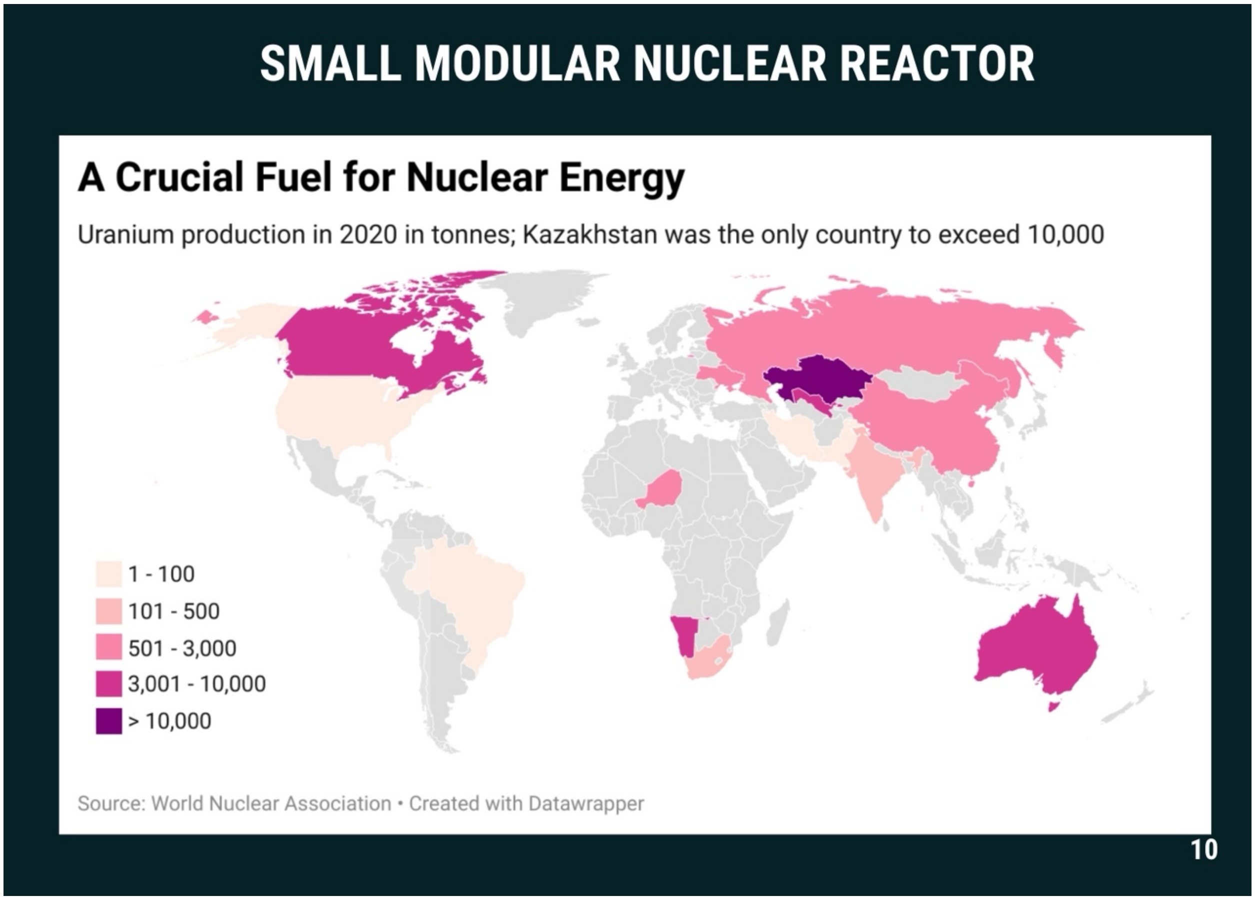
LIKELY COMMERCIALLY AVAILABLE BY 2028



Companies with viable prototypes

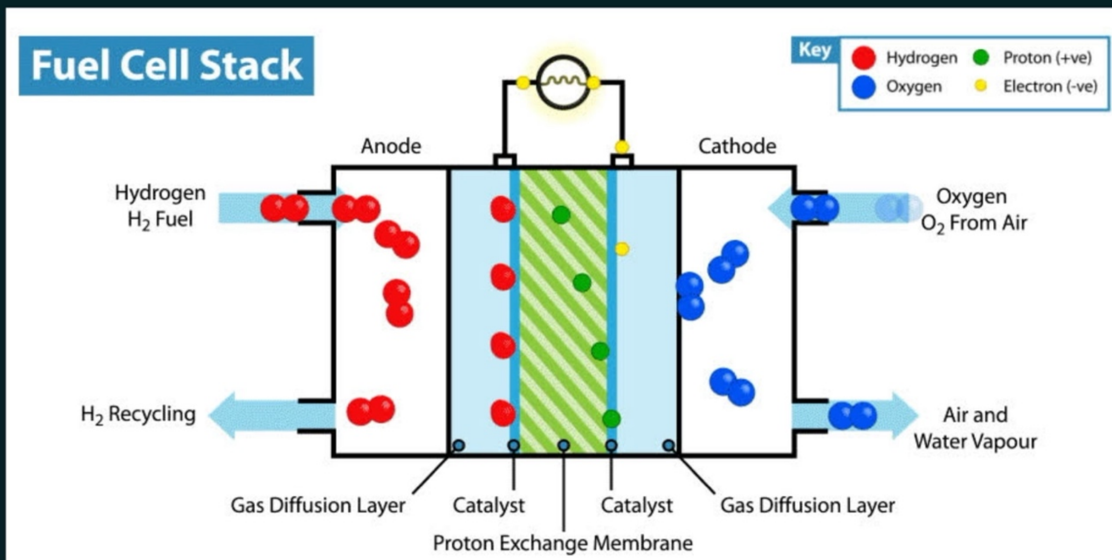
NUSCALE
TerraPower
Westinghouse
BWXT

9


SMALL MODULAR NUCLEAR REACTOR
A Crucial Fuel for Nuclear Energy
Uranium production in 2020 in tonnes; Kazakhstan was the only country to exceed 10,000
1 - 100
101 - 500
501 - 3,000
3,001 - 10,000
> 10,000
Source: World Nuclear Association • Created with Datawrapper
10

HYDROGEN FUEL CELLS

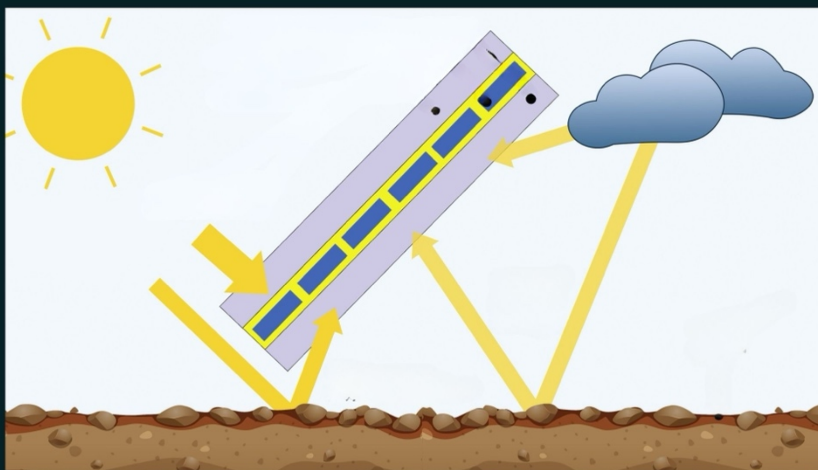
LIKELY COMMERCIALLY AVAILABLE BY 2026



12

ADVANCED BI-FACIAL SOLAR PANELS

LIKELY COMMERCIALLY AVAILABLE BY 2029



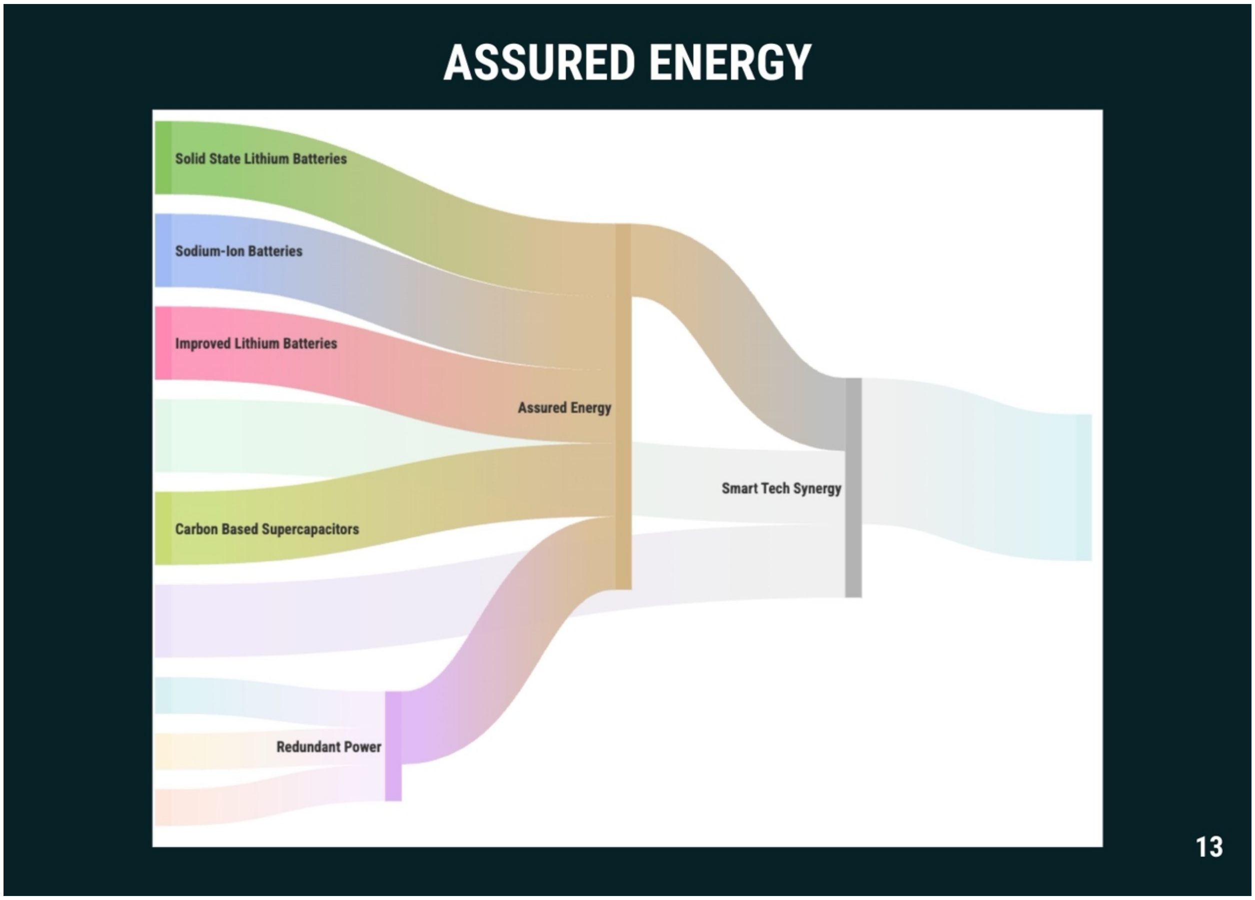
Over 30 startups

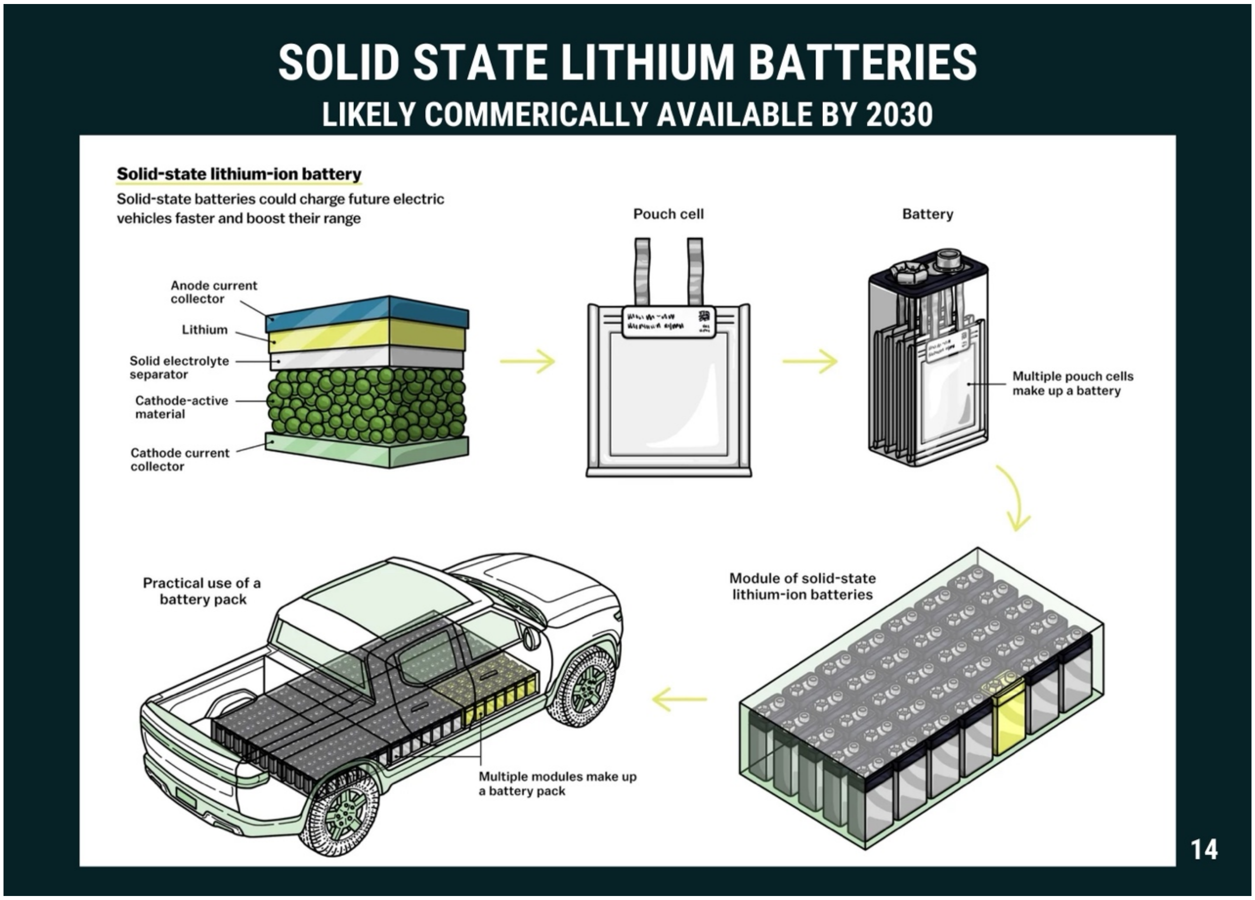
Leading companies in initial stages:

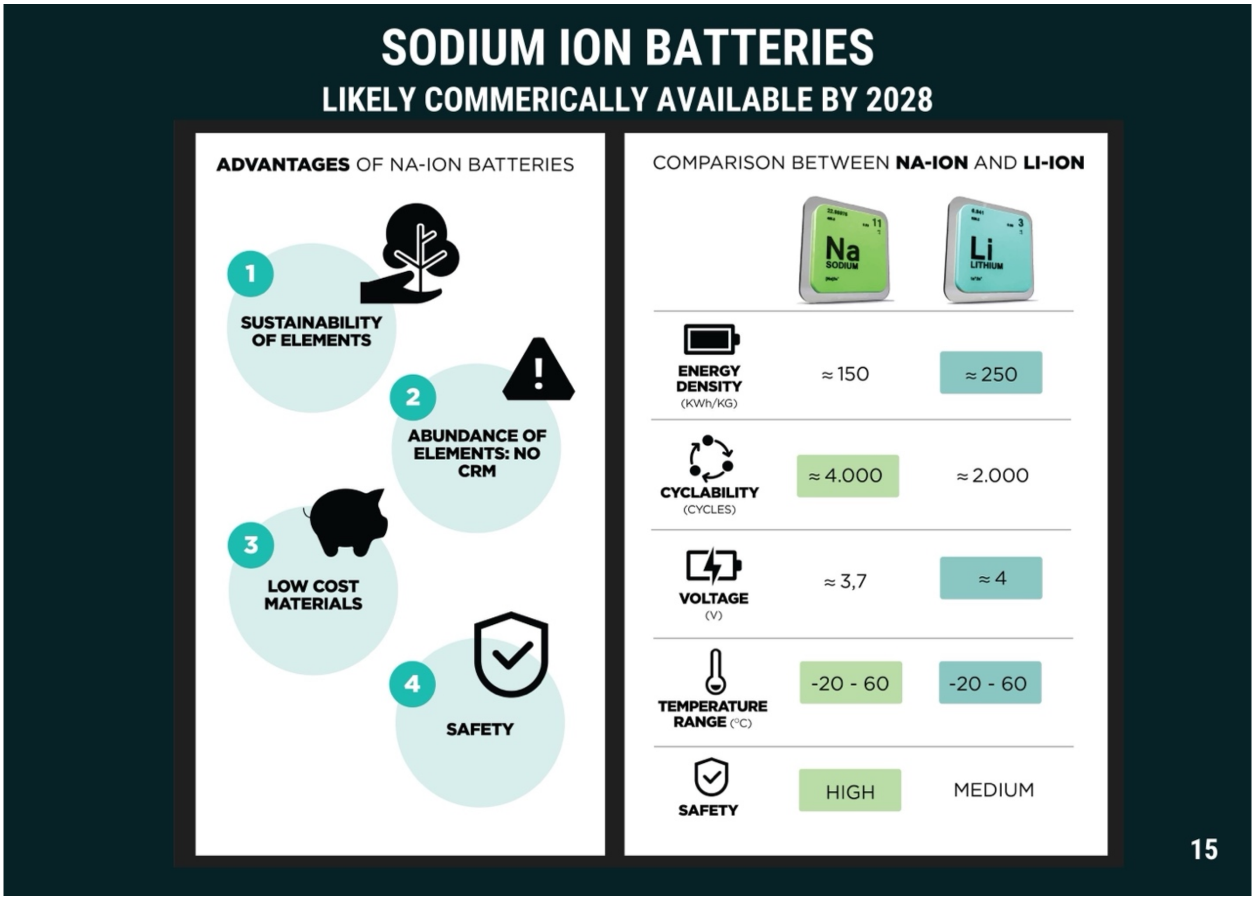
Hanwha Q CELLS
Microquanta Semiconductor
Oxford PV
Greatcell Energy
Saule Technologies

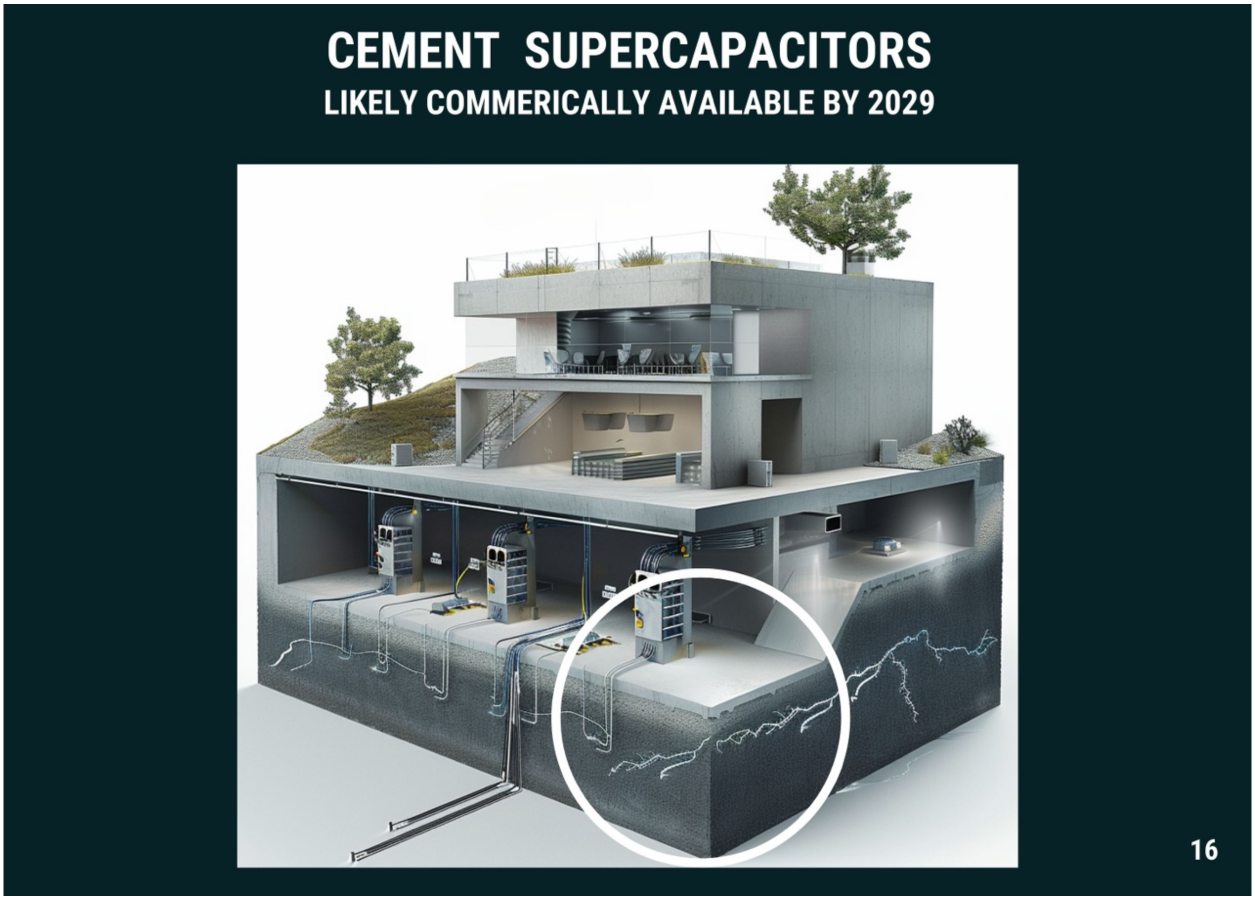
***No US-based companies**

11


ASSURED ENERGY
Solid State Lithium Batteries
Sodium-Ion Batteries
Improved Lithium Batteries
Assured Energy
Carbon Based Supercapacitors
Smart Tech Synergy
Redundant Power
13


SOLID STATE LITHIUM BATTERIES
LIKELY COMMERICALLY AVAILABLE BY 2030
Solid-state lithium-ion battery
Solid-state batteries could charge future electric vehicles faster and boost their range
Pouch cell
Battery
Anode current collector
Lithium
Solid electrolyte separator
Cathode-active material
Cathode current collector
Multiple pouch cells make up a battery
Practical use of a battery pack
Module of solid-state lithium-ion batteries
Multiple modules make up a battery pack
14


SODIUM ION BATTERIES
LIKELY COMMERICALLY AVAILABLE BY 2028
ADVANTAGES OF NA-ION BATTERIES
1
SUSTAINABILITY OF ELEMENTS
2
ABUNDANCE OF ELEMENTS: NO CRM
3
LOW COST MATERIALS
4
SAFETY
COMPARISON BETWEEN NA-ION AND LI-ION
Na
SODIUM
Li
LITHIUM
ENERGY DENSITY (KWh/KG)
≈ 150
≈ 250
CYCLABILITY (CYCLES)
≈ 4.000
≈ 2.000
VOLTAGE (V)
≈ 3,7
≈ 4
TEMPERATURE RANGE (°C)
-20 - 60
-20 - 60
SAFETY
HIGH
MEDIUM
15


CEMENT SUPERCAPACITORS
LIKELY COMMERICALLY AVAILABLE BY 2029
16

IMPROVED LITHIUM BATTERIES

LIKELY COMMERCIALLY AVAILABLE BY 2030

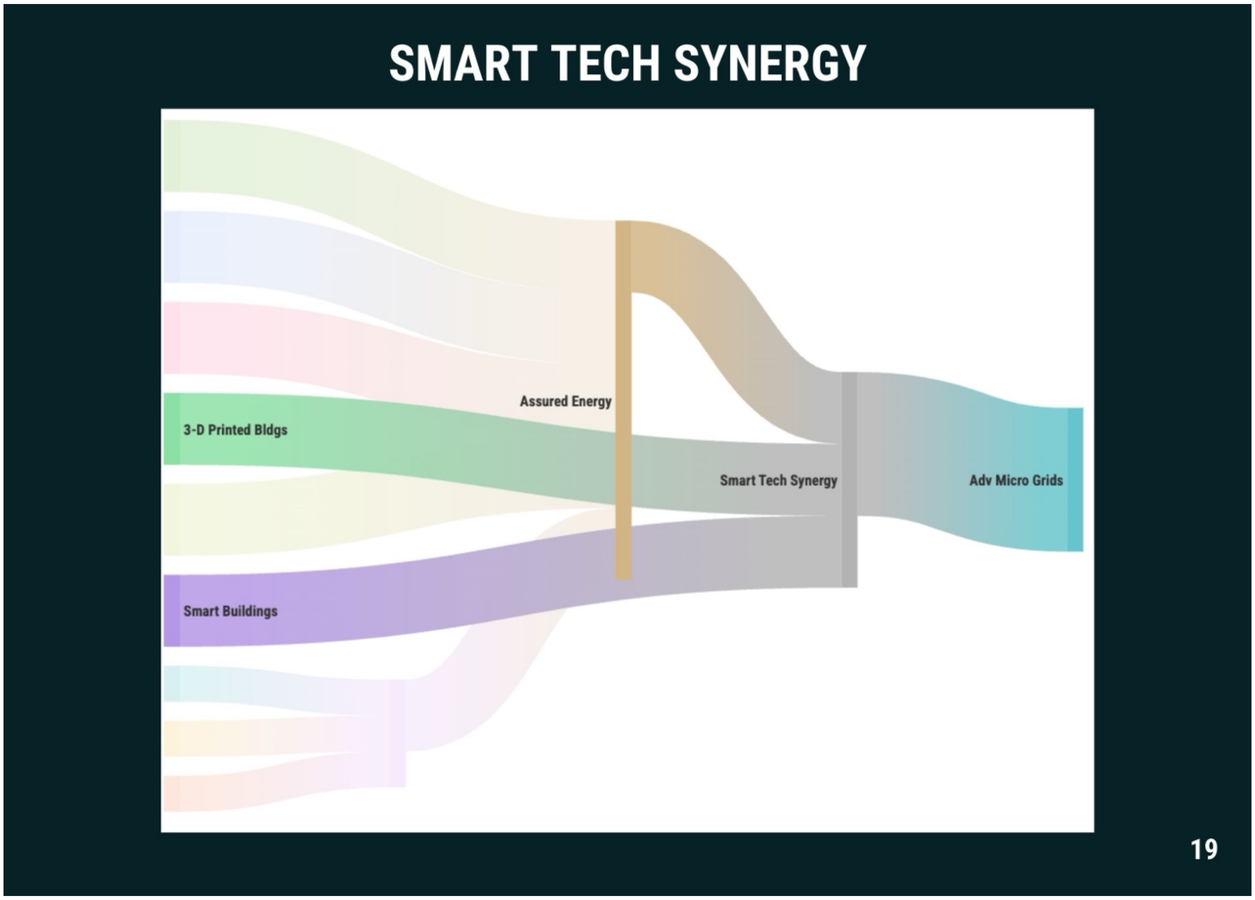
REDUCED RELIANCE ON RARE EARTH ELEMENTS

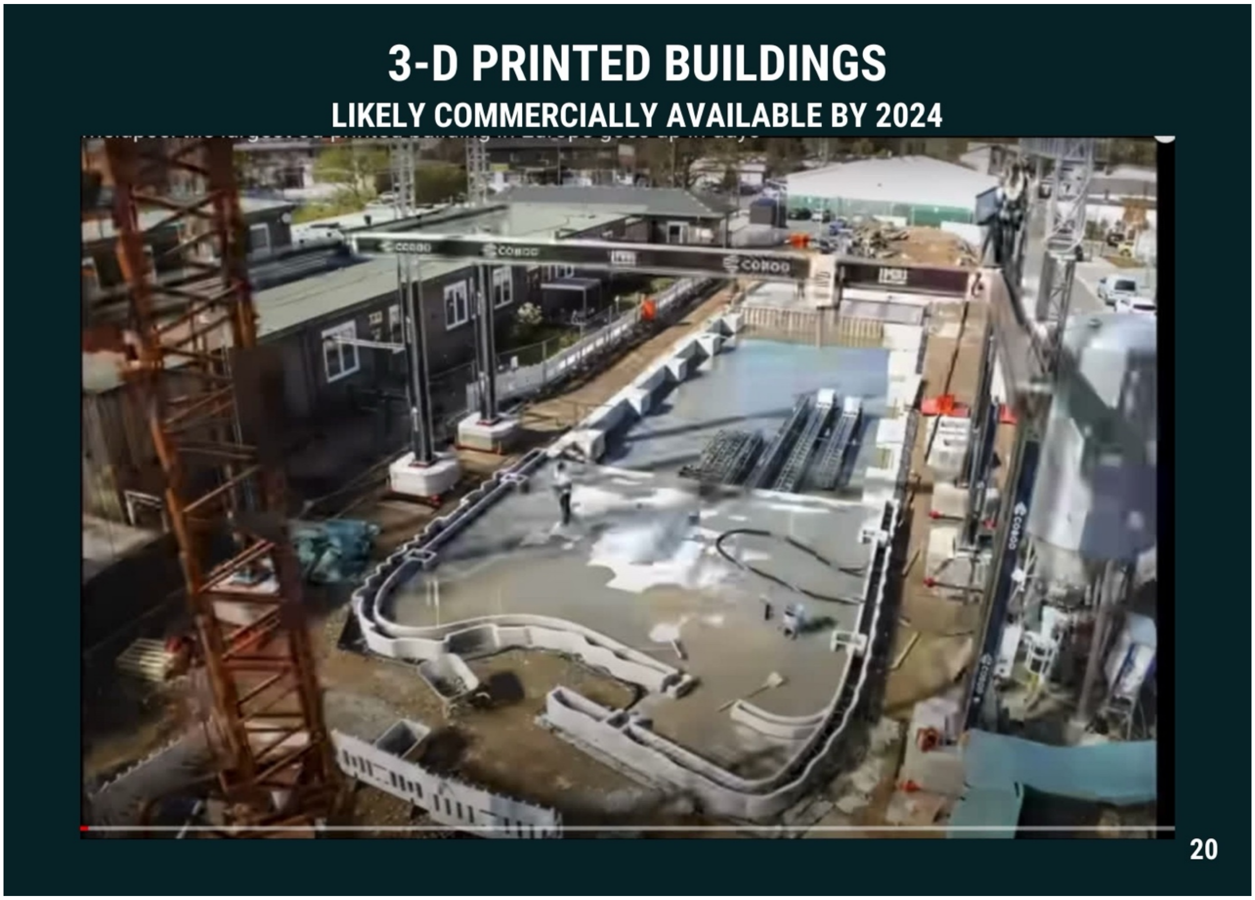
FASTER DISCHARGE RATE

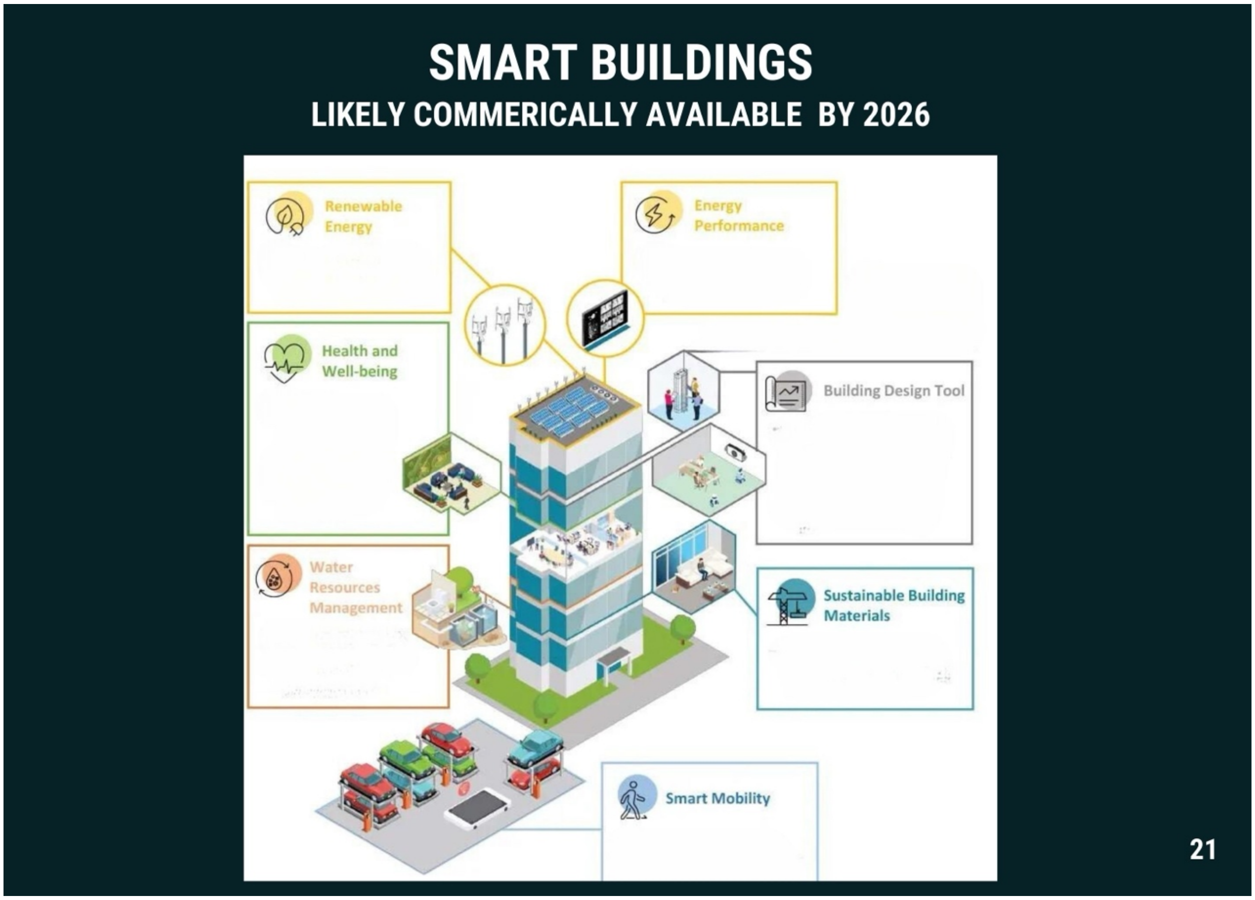
LONGER LIFESPAN

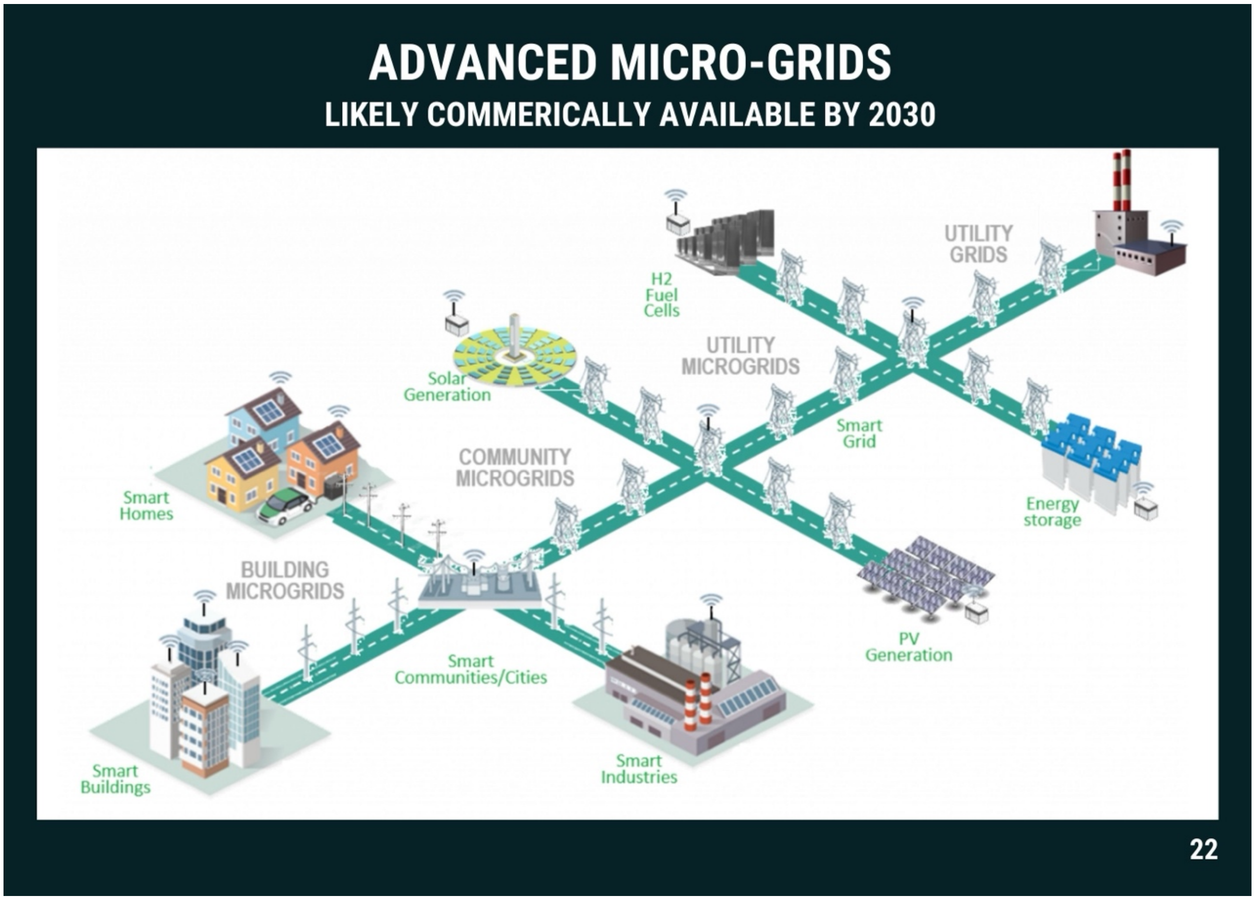
17


MEDIUM VEHICLE HYBRIDIZATION
LIKELY COMMERICALLY AVAILABLE BY 2024
18

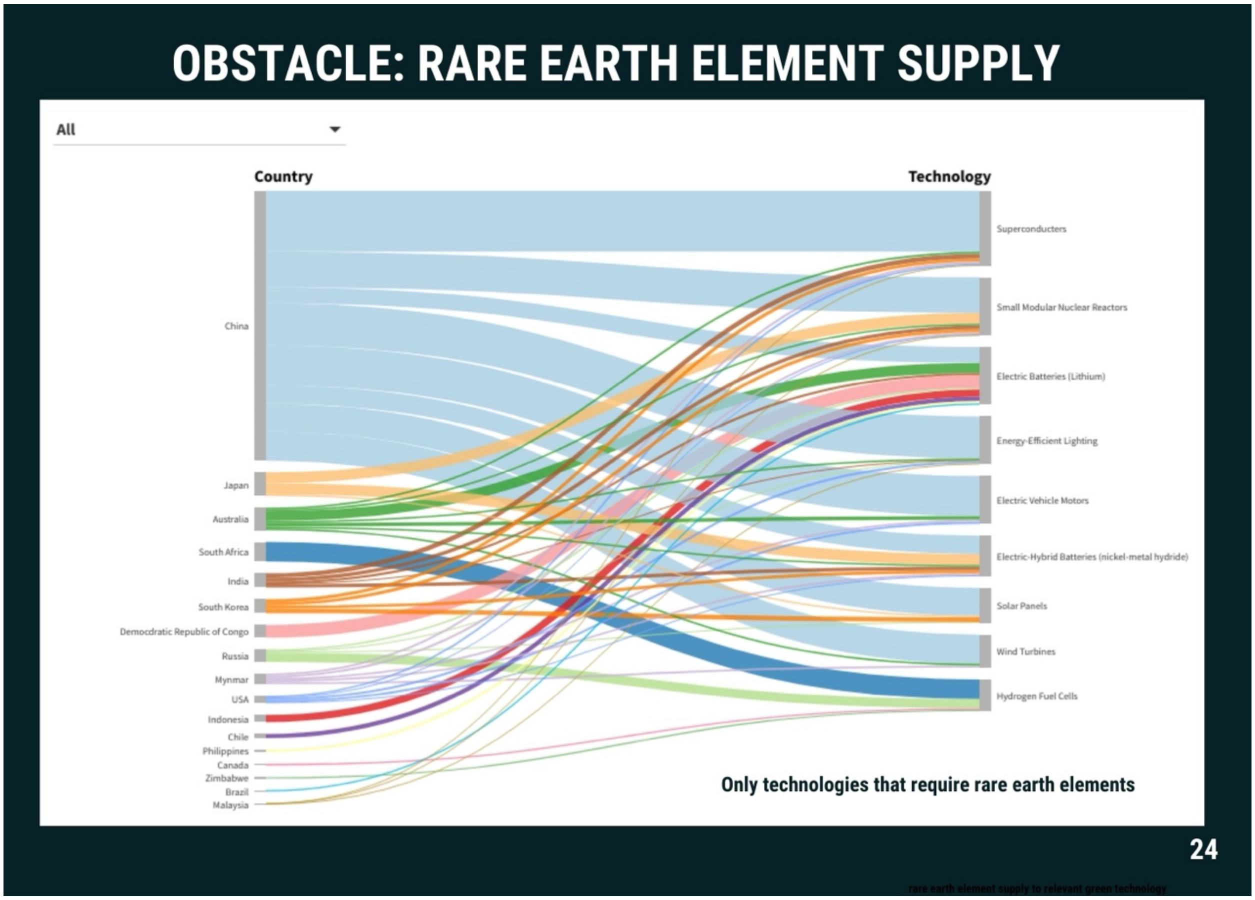

SMART TECH SYNERGY
Assured Energy
3-D Printed Bldgs
Smart Tech Synergy
Adv Micro Grids
Smart Buildings
19


3-D PRINTED BUILDINGS
LIKELY COMMERCIALLY AVAILABLE BY 2024
20


SMART BUILDINGS
LIKELY COMMERICALLY AVAILABLE BY 2026
Renewable Energy
Energy Performance
Health and Well-being
Building Design Tool
Water Resources Management
Sustainable Building Materials
Smart Mobility
21


ADVANCED MICRO-GRIDS
LIKELY COMMERICALLY AVAILABLE BY 2030
H2
Fuel
Cells
UTILITY
GRIDS
UTILITY
MICROGRIDS
Solar
Generation
Smart
Grid
COMMUNITY
MICROGRIDS
Smart
Homes
Energy
storage
BUILDING
MICROGRIDS
PV
Generation
Smart
Communities/Cities
Smart
Buildings
Smart
Industries
22

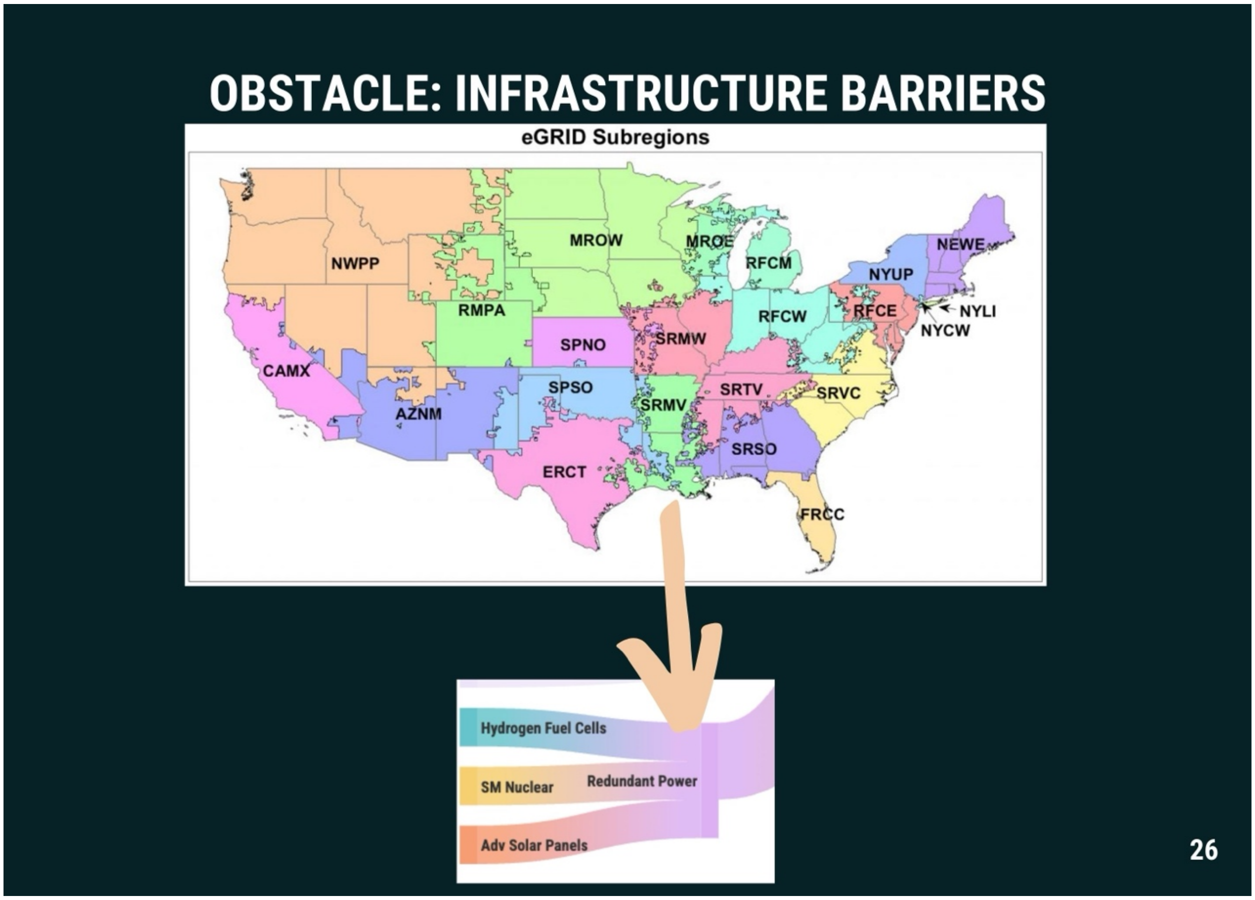

OBSTACLES
23


OBSTACLE: RARE EARTH ELEMENT SUPPLY
All
Country
Technology
China
Japan
Australia
South Africa
India
South Korea
Democdratic Republic of Congo
Russia
Mynmar
USA
Indonesia
Chile
Philippines
Canada
Zimbabwe
Brazil
Malaysia
Superconducters
Small Modular Nuclear Reactors
Electric Batteries (Lithium)
Energy-Efficient Lighting
Electric Vehicle Motors
Electric-Hybrid Batteries (nickel-metal hydride)
Solar Panels
Wind Turbines
Hydrogen Fuel Cells
Only technologies that require rare earth elements
24
rare earth element supply to relevant green technology

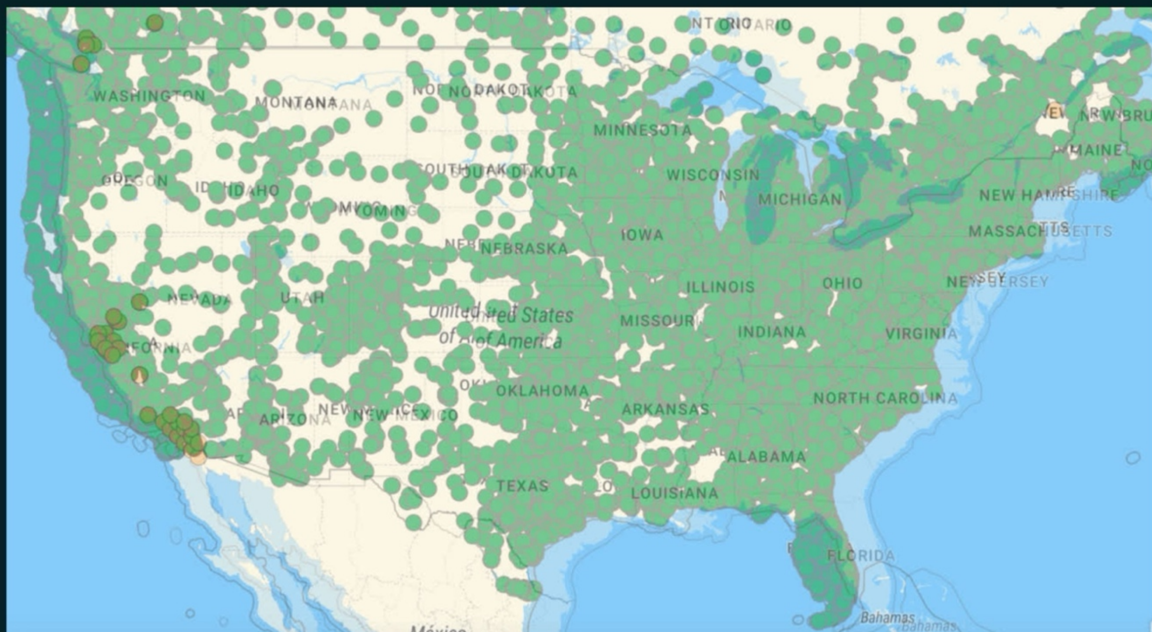
TECHNOLOGIES NOT RELIANT ON RARE EARTH ELEMENTS FROM GEOPOLITICAL ADVERSARIES

HYDROGEN FUEL CELLS
SODIUM ION BATTERIES
CEMENT SUPERCAPACITORS
3-D PRINTED BUILDINGS
LITHIUM BATTERIES (AUSTRALIA)

25

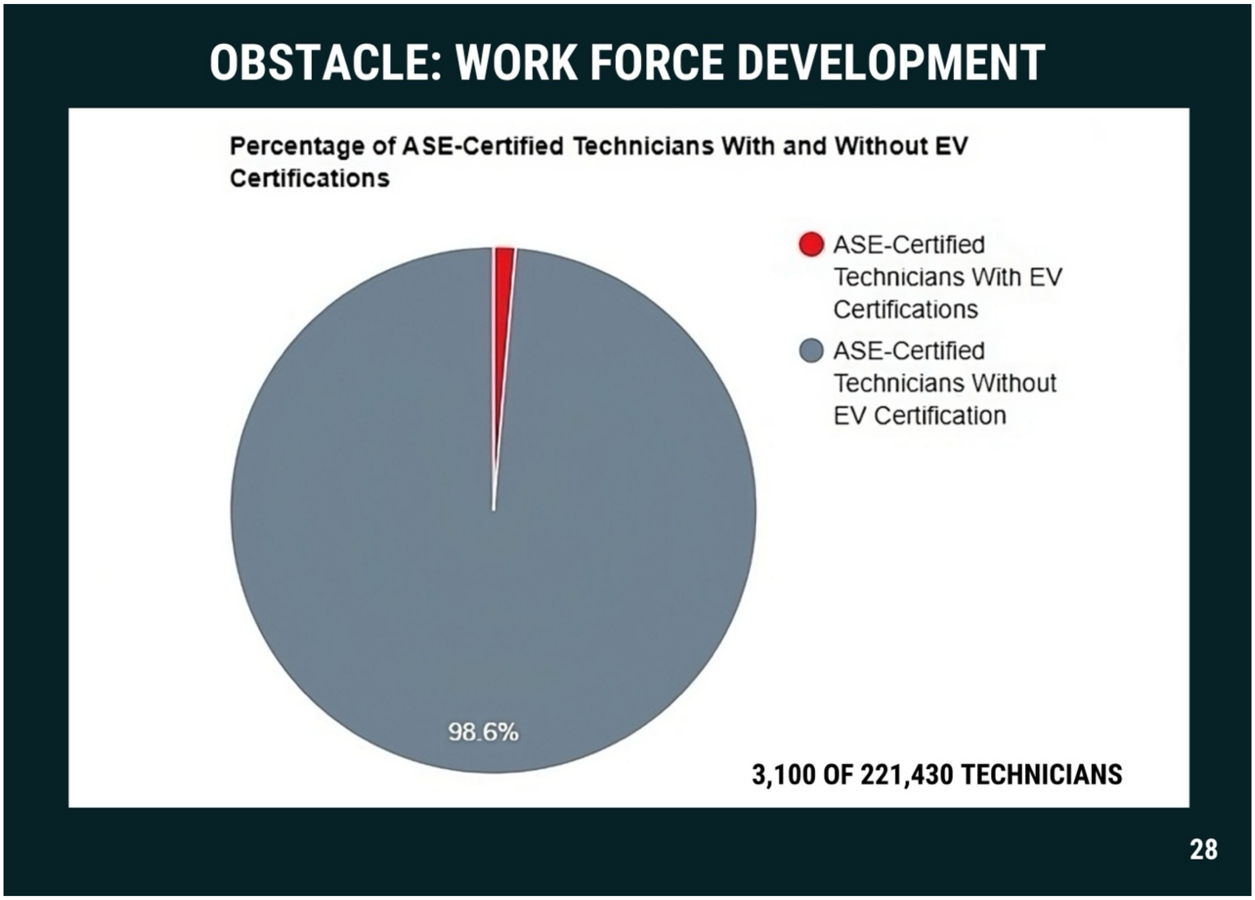

OBSTACLE: INFRASTRUCTURE BARRIERS
eGRID Subregions
NWPP
MROW
MROE
RFCM
NEWE
NYUP
RMPA
RFCW
RFCE
NYLI
NYCW
SPNO
SRMW
CAMX
SPSO
SRTV
SRVC
AZNM
SRMV
SRSO
ERCT
FRCC
Hydrogen Fuel Cells
SM Nuclear
Redundant Power
Adv Solar Panels
26

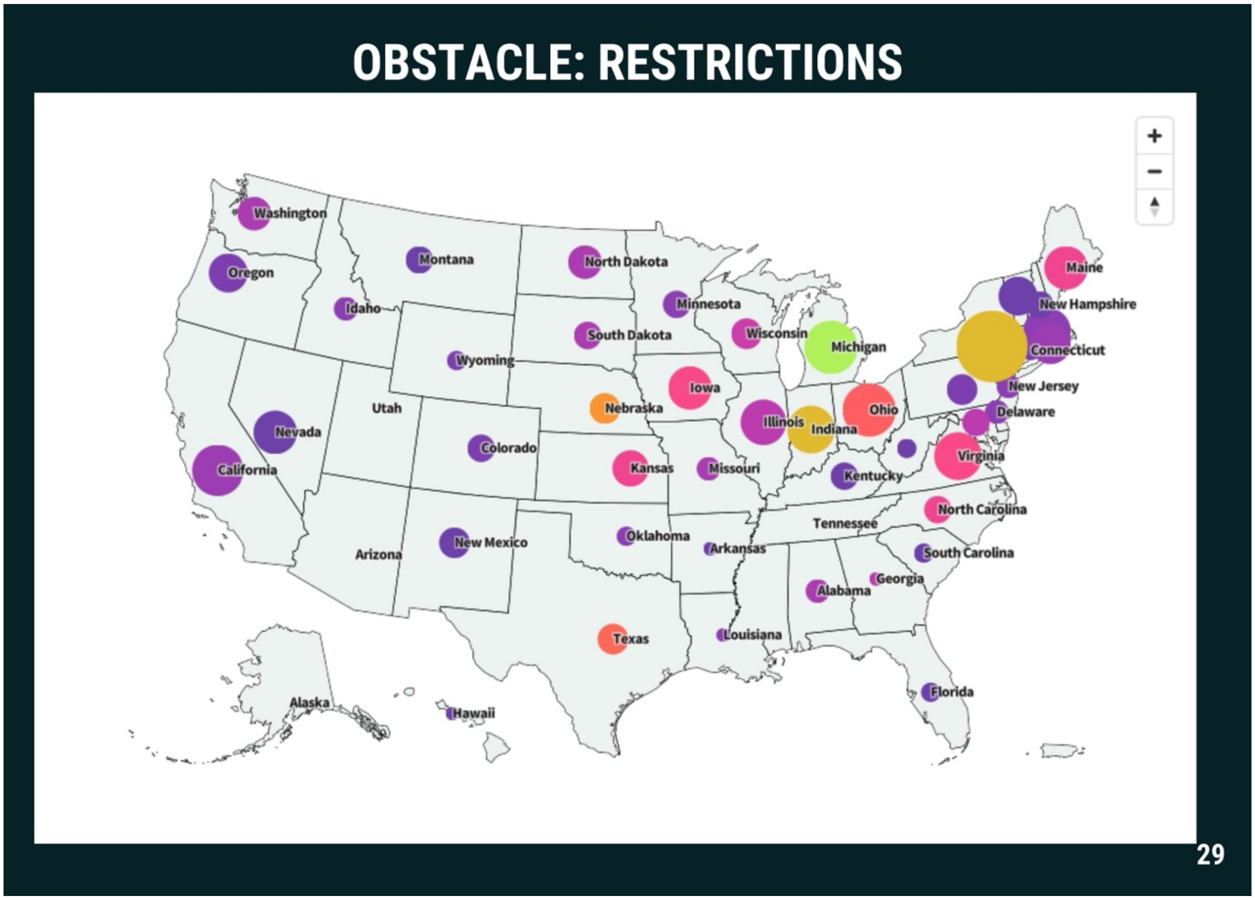
OBSTACLE: INFRASTRUCTURE BARRIERS

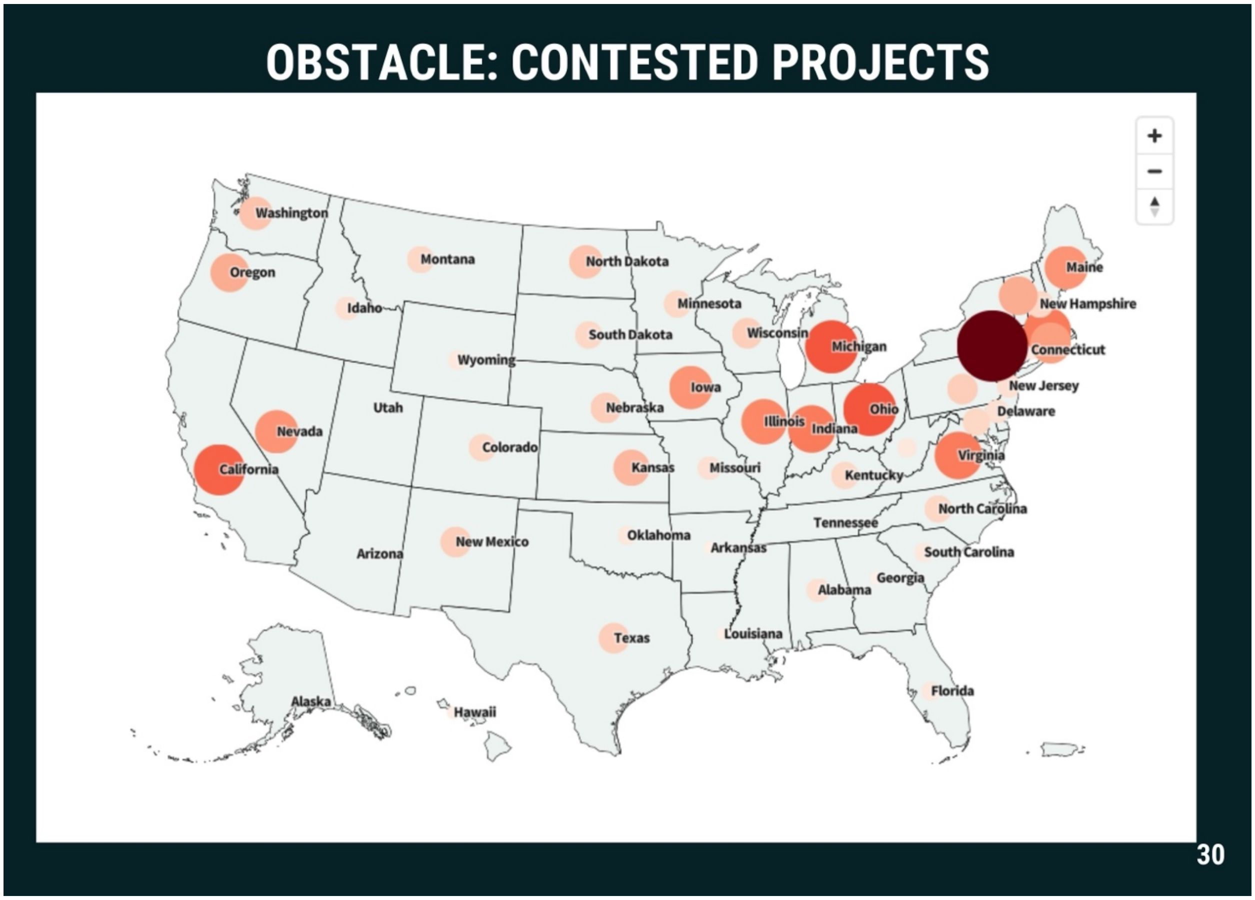


ELECTRIC VEHICLE (GREEN) VS HYDROGEN (ORANGE) CHARGING STATIONS

27


OBSTACLE: WORK FORCE DEVELOPMENT
Percentage of ASE-Certified Technicians With and Without EV Certifications
ASE-Certified Technicians With EV Certifications
ASE-Certified Technicians Without EV Certification
98.6%
3,100 OF 221,430 TECHNICIANS
28


OBSTACLE: RESTRICTIONS
Washington
Oregon
Idaho
Montana
North Dakota
Minnesota
South Dakota
Wyoming
Wisconsin
Michigan
Maine
New Hampshire
Connecticut
New Jersey
Delaware
Iowa
Nebraska
Utah
Nevada
California
Colorado
Illinois
Indiana
Ohio
Virginia
Kansas
Missouri
Kentucky
North Carolina
Tennessee
Oklahoma
Arkansas
New Mexico
Arizona
South Carolina
Georgia
Alabama
Texas
Louisiana
Florida
Alaska
Hawaii
29


OBSTACLE: CONTESTED PROJECTS
Washington
Oregon
Montana
North Dakota
Idaho
Minnesota
South Dakota
Wisconsin
Michigan
Wyoming
Iowa
Nebraska
Utah
Nevada
Illinois
Indiana
Ohio
Colorado
California
Kansas
Missouri
Kentucky
Virginia
Maine
New Hampshire
Connecticut
New Jersey
Delaware
North Carolina
Tennessee
Oklahoma
Arkansas
New Mexico
Arizona
South Carolina
Georgia
Alabama
Texas
Louisiana
Florida
Alaska
Hawaii
30

OBSTACLE: COST OF TRANSITION

INSTALLATION PERSPECTIVE

Burlington VT Net Zero by 2030

COST TO DATE: $60M IN BONDS, TAX REBATES

SIZE: 44,0000

APPROXIMATE SIZE OF FORT CAMPBELL

31

OBSTACLE: COST OF TRANSITION

ENTERPRISE PERSPECTIVE

Net Zero Value Chain

COST TO DATE: $3.5B

	Google	Army
Locations	187	750
Countries	50	80
Employees	182,502	~460,000

UNABLE TO ACHIEVE NET ZERO IN ALL LOCATIONS DUE TO LOCAL RESTRICTIONS

SUMMARY

Emergent Capability Domains		
Redundant Power Generation	**Assured Energy**	**Smart Tech Synergy**
Small Modular Nuclear Reactors	Solid State Lithium Batteries	3D Printed Buildings
Advanced Bi-Facial Solar Panels	Hybridized Medium Size Vehicles	Smart Buildings
Large Vehicle Hydrogen Fuel Cells	Sodium-Ion Batteries	Advanced Microgrids
	Cement Supercapacitors	
	Improved Lithium-Ion Batteries	

32

QUESTIONS

Team Atropos

33