The National Academies of SCIENCES ENGINEERING MEDICINE

POWERING

THE U.S. ARMY OF THE FUTURE

Overall Objective

A study to find out what are the emerging technology options in energy/power to best suit the Army's operational requirements in 2035 and beyond. This entails bringing sufficient energy to the field and conserving its use while maintaining or enhancing the Army's warfighting capabilities.

Duo-Fold Focus Approach

Technologies

- Batteries
- Fuel Cells
- Nuclear Fission
- Radioisotope Decay
- Internal Combustion Engines
- Turbines
- Thermophotovoltaic
- Alternative (Wind, Solar, etc.)

Applications/Uses

- Dismounted Soldiers
- Unmanned Ground/Air Vehicles
- Ground Combat Vehicles
- Tactical Vehicles
- Forward Operating Bases
- Permanent Installations

Heaviest Focus on Armored Brigade Combat Team as most demanding application. Avoided spending much time on permanent installations as they are not so unique from the commercial sector.

Overall Study Objectives

Meet growing power need

Reduce fuel transport burden

Reduce weight (soldiers, vehicles, equipment)

Be environmentally friendly (where practical)

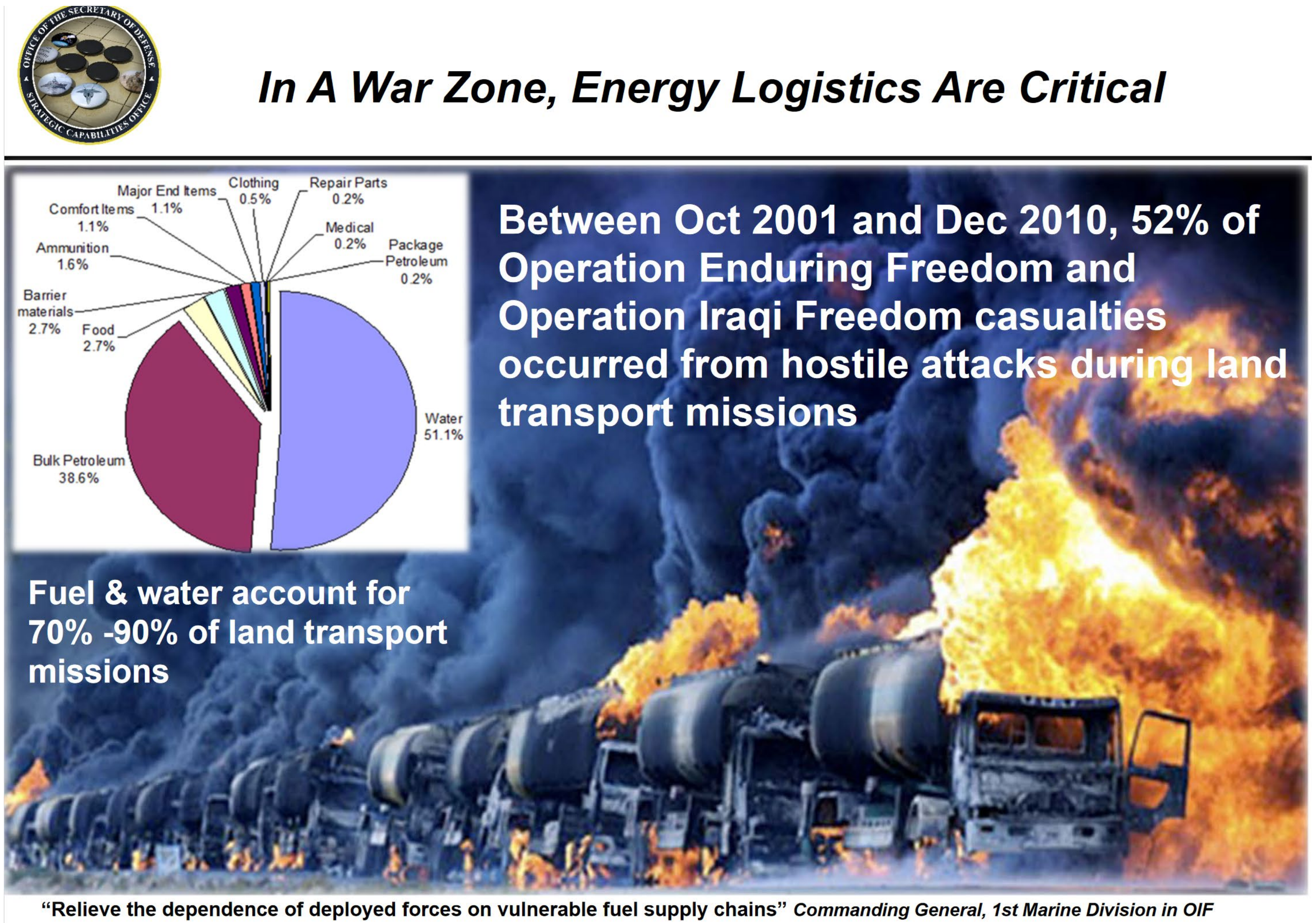
Maintain ability to lock-out seized resources

Provide rapid asset mobility

Increase self-sustainability 3 -> 7 days

Reduce or maintain refueling/recharging times

Provide greatest operational advantage on the battlefield



In A War Zone, Energy Logistics Are Critical

Between Oct 2001 and Dec 2010, 52% of Operation Enduring Freedom and Operation Iraqi Freedom casualties occurred from hostile attacks during land transport missions

Fuel & water account for 70% -90% of land transport missions

"Relieve the dependence of deployed forces on vulnerable fuel supply chains" ***Commanding General, 1st Marine Division in OIF***

Source: Project Pele Overview, Mobile Nuclear Power for Future DoD Needs, March 2020, Office of the Secretary of the Defense; Strategic Capabilities Office

Previous Studies Advocating Nuclear Power and Battery Electric Vehicles

> ***“Unleash us from the tether of fuel.”***
>
> *— Gen. James Mattis, former commander of the*
> *1st Marine Division, during the drive to Baghdad, March 2003*

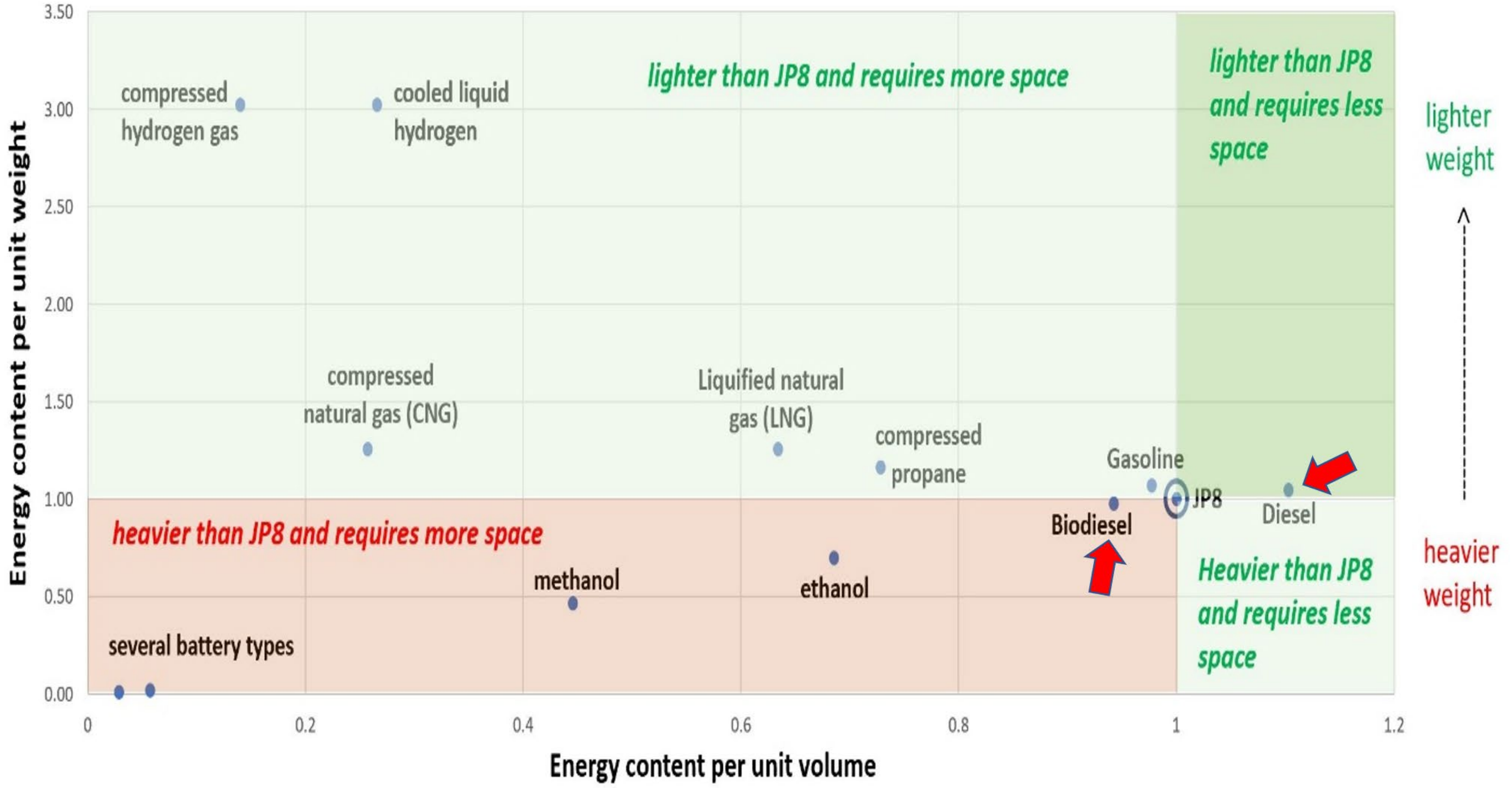
Employment of mobile nuclear power is consistent with the new geopolitical landscape and priorities outlined in the US National Security Strategy (NSS) and the 2018 National Defense Strategy focusing on China and Russia as the principal priorities for the U.S. Department of Defense (DOD)… This study finds that as a technical matter, nuclear power can reduce supply vulnerabilities and operating costs while providing a sustainable option for reducing petroleum demand and focusing fuel forward to support Combatant Commander (CCDR) priorities and maneuver in multi-domain operations (MDO).

Study on the Use of Mobile Nuclear Plants
Deputy Chief of Staff, G-4
October 26, 2018

‘‘Powering the Army of 2035’’ In One Slide

- There are many realistic opportunities to reduce fuel transported to the field by up to 1/3. **Liquid hydrocarbon fuels will remain the main source of combined energy and power brought to the battlefield through 2035.**
- Electrification of ground combat vehicles is highly desirable, but it should take the form of **hybrid electric vehicles (with internal combustion engines)**, not all battery electric vehicles.
- **Mobile nuclear plants powering battery electric combat vehicles will require a significantly longer timeframe than 2035** due to: 1) a mismatch between the power available and the power need, 2) vehicle package and weight penalties, and 3) a mismatch between the mobility they offer and what is needed for multi-domain operations.
- **New battery chemistries** offer increased flexibility in the tradeoffs between energy storage, power delivery, rapid charging, and safety. Ongoing S&T studies should be a high priority.
- Investment to achieve **further advances in fuel cells, JP8 fuel reformers, radioisotope decay devices, photovoltaic/combustion hybrids, and onsite hydrogen production** may provide additional capabilities.
- **Power and energy logistics considerations should be added to wargaming simulations** to ensure the options being pursued by the Army are realistic for any given timeframe.

Energy Density Comparison of Transportation Fuels (indexed to JP8 = 1)



requires more storage space --> requires less storage space

requires more fuel transport trucks --> requires fewer fuel transport trucks

SOURCE: U.S. EIA. 2013. Few transportation fuels surpass the energy densities of gasoline and diesel. Committee-built chart using data from this source. U.S. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=9991. Accessed November 2020.

Major Energy Sources

- JP-8, diesel, and/or biodiesel will continue to serve as the primary source of battlefield energy and power for the foreseeable future.
- The technology (closed loop combustion) exists today to seamless transition between these three fuels.
- On the battlefield, diesel could be the preferred fuel to minimize fuel transport due to its 9% higher volumetric energy content and possible local availability.
- JP8 (or JP4 or JP5) could be the preferred battlefield fuel where required due to climatic conditions or commonality with aircraft.
- Biodiesel (or other sustainable fuel sources) could be the preferred fuel for domestic use and during peacetime due to its environmental advantages.
- The benefits of these fuel alternatives would require revisions to the Army's "single fuel policy" and would need to be weighed against the associated logistics complexity penalties.

2035 and Earlier Opportunities To Reduce Fuel Transport

	Fuel Efficiency		
Internal Combustion Engine	28%	improvement	39% BTE (present Army engines) to 50+% BTE (DOE SuperTruck levels)
Hybridization	10 to 20%		Opportunity size dependent upon recovery of braking energy
Diesel Fuel in lieu of JP8	9%		Higher volumetric energy density
Assorted Other	5 to 8%		Transmission/Cooling/Vehicle Parasitic Loss Improvements
Total Fuel Efficiency Improvement	35 to 48%	improvement	Resulting in less risk of life during fuel transportation

- A 48% improvement in fuel efficiency results in a 32% reduction in the fuel needed to be transported to the field for a given mission.

BTE – Brake Thermal Efficiency

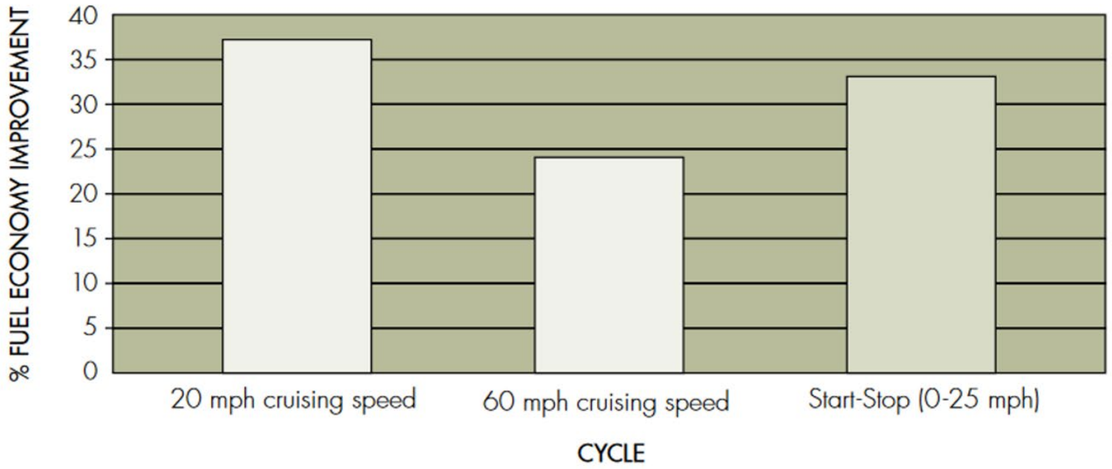
Present Production Ground Combat Vehicle Hybrid

Oshkosh Propulse Hybrid Diesel-Electric Vehicle

Can export 120 kW of electrical power while stationary.

SOURCE: Oshkosh Defense. Undated. Hybrid Diesel-Electric System. Online. https://oshkoshdefense.com/wp-content/uploads/2019/02/ProPulse_SS_6-13-11.pdf. Accessed November 2020.

PROPULSE® | HYBRID DIESEL-ELECTRIC SYSTEM



M1120 DIESEL-ELECTRIC HEMTT A3 FUEL ECONOMY TEST RESULTS

Comparison against conventional driveline vehicle
Preliminary Oshkosh internal test data

Armored Brigade Combat Team Energy Consumption Overview

(12-day Operation)

Fuel Usage: 514,464 gallons of JP8
equivalent to: 18,800 MWh of chemical energy

Battery Usage: 69,046 batteries
equivalent to: 2.5 MWh of electrical energy

Average Power Expenditure: 18,800 MWh / 288 hours = 65 MW
Peak Power Expenditures: Not available, but much higher

Westinghouse DeVinci™ MNPP output = 1 to 2 MW

Number of MNPP's required for 1 ABCT
(w/ energy storage for peak demand) 32 to 65

Source: RAND Corporation Presentation to the study committee. The Operational Logistics (OPLOG) Planner is the main tool provided by Combined Arms Support Command (CASCOM) to assess mission equipment and energy needs.

Abrams Tank: JP8 versus Battery Comparison

JP8 Fuel Summary

1900 liters
(501 gallons)

X 0.001 m³/liter → 1.90 m³ volume

X 0.80 kg/liter → 1502 kg weight

X 12.1 kWh/kg
X 0.80 kg/liter
→ 18,400 kWh
JP8 fuel energy

ICE Efficiency	39%
Trans Efficiency	82%
Cooling	85%

Combined
Efficiency
27.2%

Comparison

1.90 m³ volume → **≈ 22 times** → 41.8 m³ volume

1502 kg weight → **≈ 20 times** → 30,600 kg weight

BEV Summary

41.8 m³ volume
X 1000 liter/m³
X 0.220 kWh/liter
→ 9,190 kWh
Total BEV Energy

30,600 kg weight
X 0.300 kWh/kg
→ 9,190 kWh
Total BEV Energy

X 0.8 → 7,350 kWh
Usable BEV Energy
(w/ 20% reserve)

Power Transfer	85%
Cooling	80%

Combined
Efficiency
68.0%

5000 kWh
Energy Delivered To Sprockets
For full range (265 miles road/124 miles cross-country)

Army Maneuver and Nuclear Power

- OSD's Strategic Capabilities Office has noted *"mobile nuclear power will allow a transformation in capabilities for the future warfighter"*
  - Project Pele is developing a full prototype mobile nuclear reactor to determine the feasibility for future technology transitions.
  - Project Pele focus includes understanding its potential utility in a basecamp setting.
- The community also has stressed the potential of nuclear power to also ease fuel logistics.
- The role and vulnerability of fixed bases is an open question in future Multi-Domain Operations (MDO) against peer adversaries

Using the Project Pele aspirational power goal as a baseline suggests that MDO exploitation of nuclear power in all-electric ground combat vehicles will not be operationally feasible in the 2035 time frame.

Sources: 1. Project Pele Overview, Mobile Nuclear Power for Future DoD Needs, March 2020, Office of the Secretary of the Defense; Strategic Capabilities Office. 2. 2018 National Defense Strategy and National Security Strategy. 3. TRADOC briefings on MDO (March 21, 2020)

Recharging Times and Mobility Present Even Greater Challenges

Recharging Requirements

Time to recharge each 70-ton Abrams with DeVinci^{TM} MNPP = 7350 kWh/2000 kW = 3.7 hours

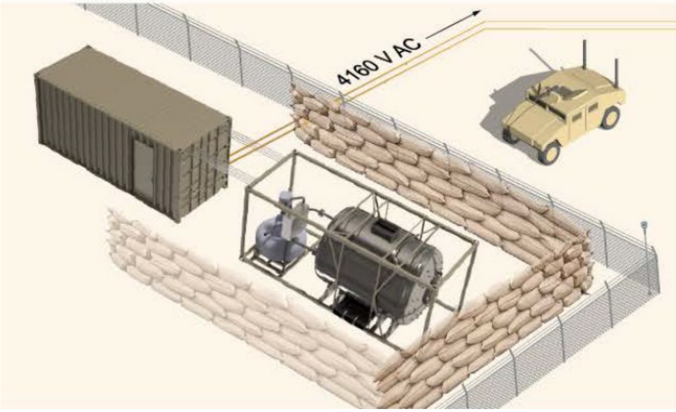
Power source required to recharge each 70-ton Abrams in 15 minutes
= (7.35 MWh x 60 min/hr)/15 min = 29 MW

Number of DeVinci^{TM} MNPP's required to recharge each Abrams in 15 minutes
= 29 MW/2MW = 14.5 MNPP's

Memo: Time to refuel an Abrams = 6 minutes

Mobility Concerns

DeVinci^{TM} Output: 1 to 2 MW
Two 20' Trailers; 39-ton total
Both fit in a C-17 Globemaster
3-day set-up time
2-day cooldown



Prior Army Battery Electric Vehicle Tank Studies

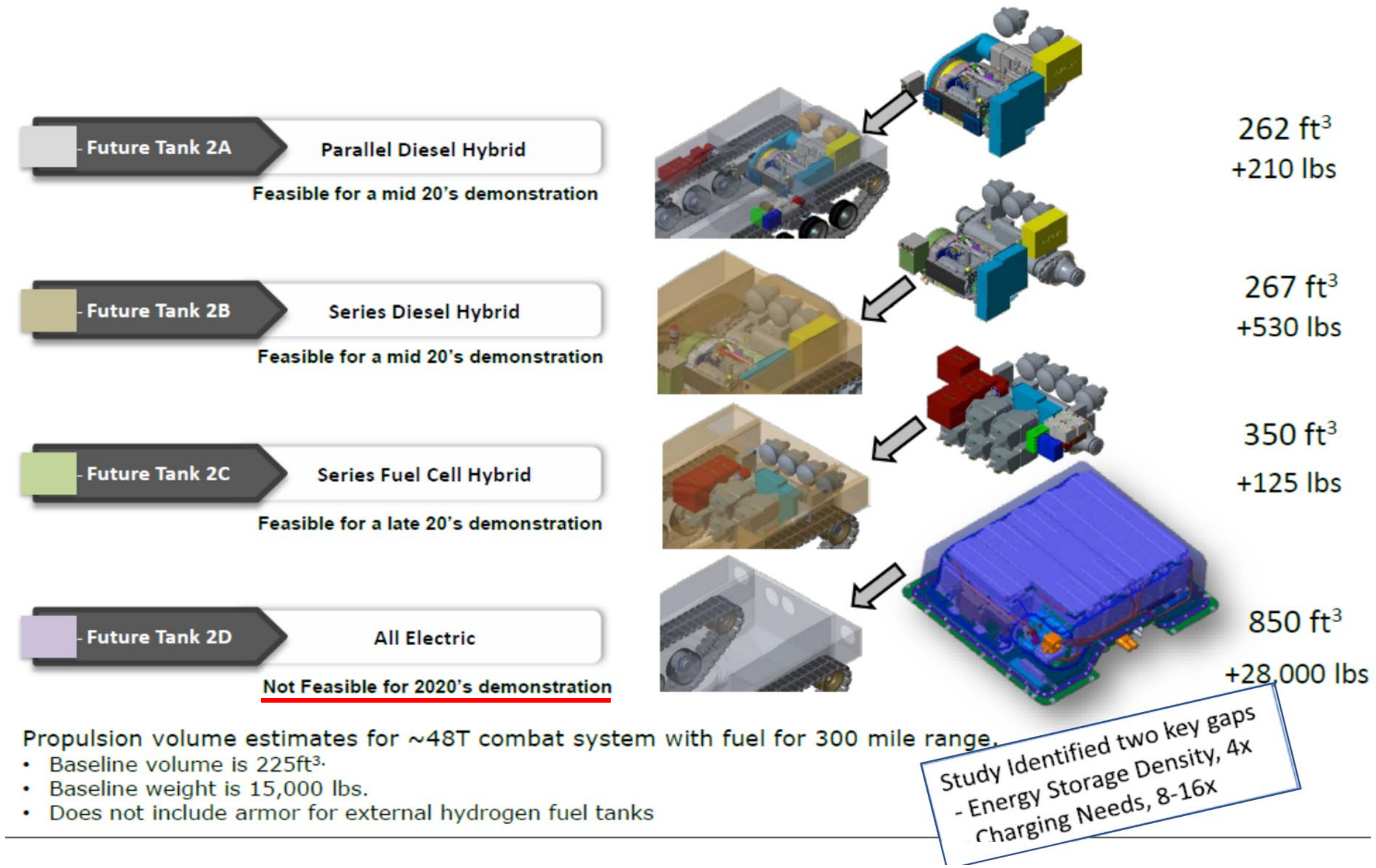
ALL ELECTRIC TANK FEASIBILITY (HYBRID VS. FULL E-TANK)

DEVCOM GROUND VEHICLE SYSTEMS CENTER

All Electric Tank (with Today's Tech)
~100,000 lbs (50 ton)
Range: 300 miles
11.5kWh/mile (3.4MWhr battery)
Battery Est. Weight: 60,100 lbs
Battery Est. Vol: 605 ft^3
*Recharge: 3.4MW (1hr), 6.8MW (30min) or **13.6MW (15min)***

This compares with 225 ft^3 available for the total powertrain.

SOURCE: Toomey, L.M. 2020. Combat Vehicle Energy Storage. Online. U.S. Army Combat Capabilities Development Command – Ground Vehicle Systems Center



Future Tank 2A	Parallel Diesel Hybrid	Feasible for a mid 20's demonstration	262 ft^3	+210 lbs
Future Tank 2B	Series Diesel Hybrid	Feasible for a mid 20's demonstration	267 ft^3	+530 lbs
Future Tank 2C	Series Fuel Cell Hybrid	Feasible for a late 20's demonstration	350 ft^3	+125 lbs
Future Tank 2D	All Electric	Not Feasible for 2020's demonstration	850 ft^3	+28,000 lbs

Propulsion volume estimates for ~48T combat system with fuel for 300 mile range.
- Baseline volume is 225ft^3.
- Baseline weight is 15,000 lbs.
- Does not include armor for external hydrogen fuel tanks

Study Identified two key gaps
- Energy Storage Density, 4x
- Charging Needs, 8-16x

SOURCE: Tylenda, J. 2020. Combat Vehicle Electrification Overview and Motivation. Online. U.S. Army Combat Capabilities Development Command – Ground Vehicle Systems Center.

Joint Light Tactical Vehicle: JP8 versus BEV Charging Time

JP8 Fuel Summary

170 liters
(45 gallons) in 2 separate tanks

X 12.1 kWh/kg
X 0.80 kg/liter

1646 kWh
JP8 fuel energy

ICE Efficiency	39%
Trans Efficiency	82%
Cooling	85%

Combined
Efficiency
27.2%

447 kWh
Energy Delivered To Wheels
For full range

BEV Equivalent

Power Source
(required to recharge in 15 minutes)*
2.63 MW

Note: Power source = 657 kWh x 60 min/hour / (15 min x 1000 kW/MW)

657 kWh
Usable BEV Energy

Power Transfer	85%
Cooling	80%

Combined
Efficiency
68%

Dismounted Soldier

Thermophotovoltaic/Battery Hybrid Device

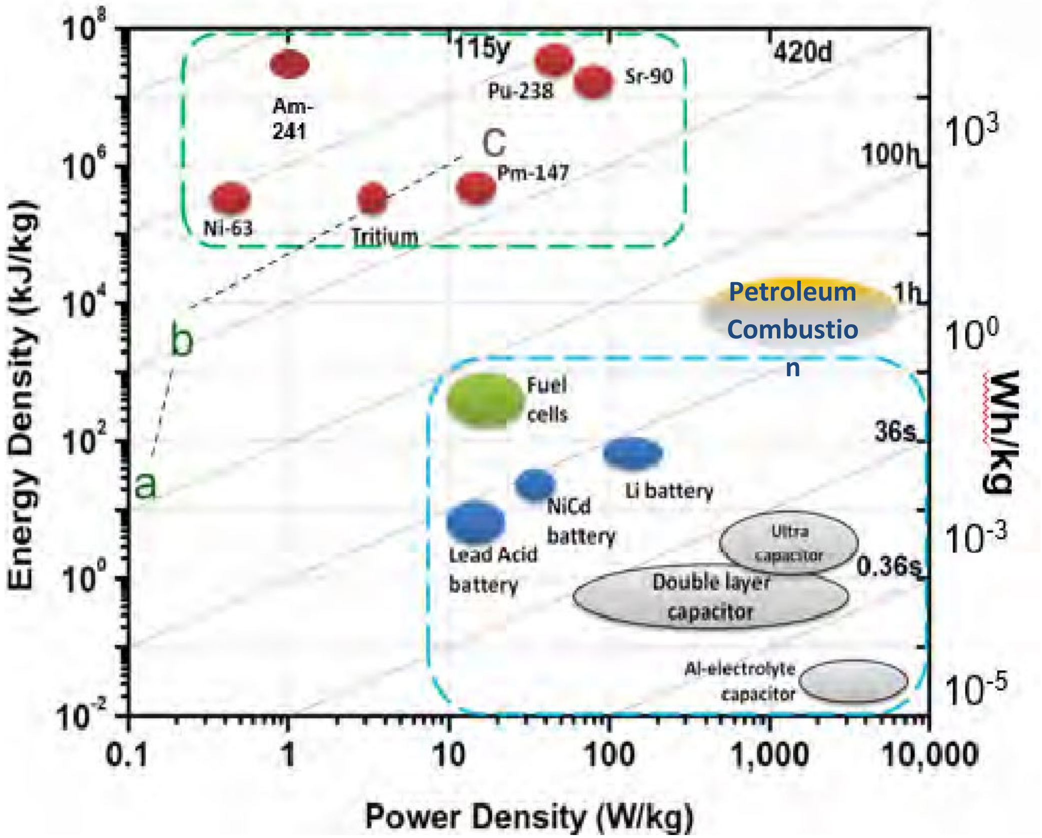
- Military Standard JP-8 fuel is relatively safe because it is hard to ignite.
- Refueling with JP-8 is a quick alternative to recharging batteries
- Because the fuel is energy dense, weight reductions of 75% can be achieved.
- The endurance of the system is about 10 times greater than batteries.
- Solid state design improves reliability over internal combustion engines

Leveraging Use of JP8 Powered Unmanned Ground Vehicles

- General Dynamics Land Systems Multi-Utility Tactical Transport (MUTT) shown
- A 10 kW JP8 based Solid Oxide Fuel Cell with a fuel reformer (desulfurization) hybridized with a battery will be tested as a primary propulsion source this year.
- Can export 3000 watts of electrical power, providing full time silent power generation
- Duplicate set of batteries would negate charging time concerns
- Note: Up to 30 kW of exportable power can be provided by other unmanned ground vehicles, such as the Pratt Miller RCV-L

Remote Sensors

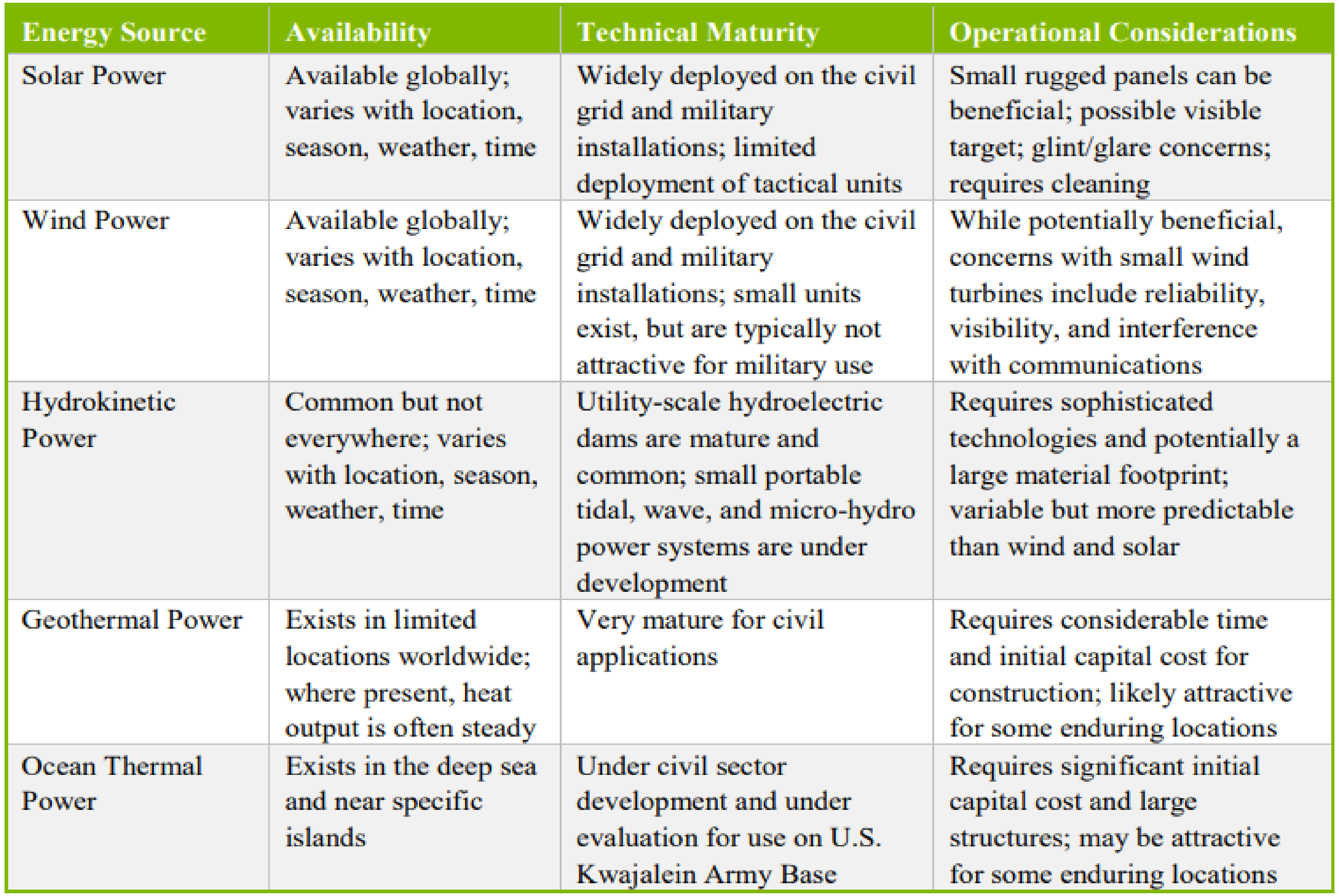
Radioisotopic Generators



- Combining a rechargeable battery with a low-power radioisotope source enables high-power operation from the battery, followed by self-recharging using the constant low power available from the radionuclide source.
- Continued study and development are recommended to identify applications where such a lightweight radioisotope decay systems could provide adequate power for present and future demands.
- The Army already has an active S&T study to efficiently transform energy-storing radioisotopes into a faster-release forms for high power output.

SOURCE: Litz, M., R. Tompkins, S. Kelley, I. Kierzewski, C. Pullen. 2020. Radioisotope Power Sources - Technology and Applications: Maximizing Beta Interactions in Textured Energy Converters. Presentation to the study committee. Combat Capabilities Development Command (CCDC), Army Research Laboratory (ARL).

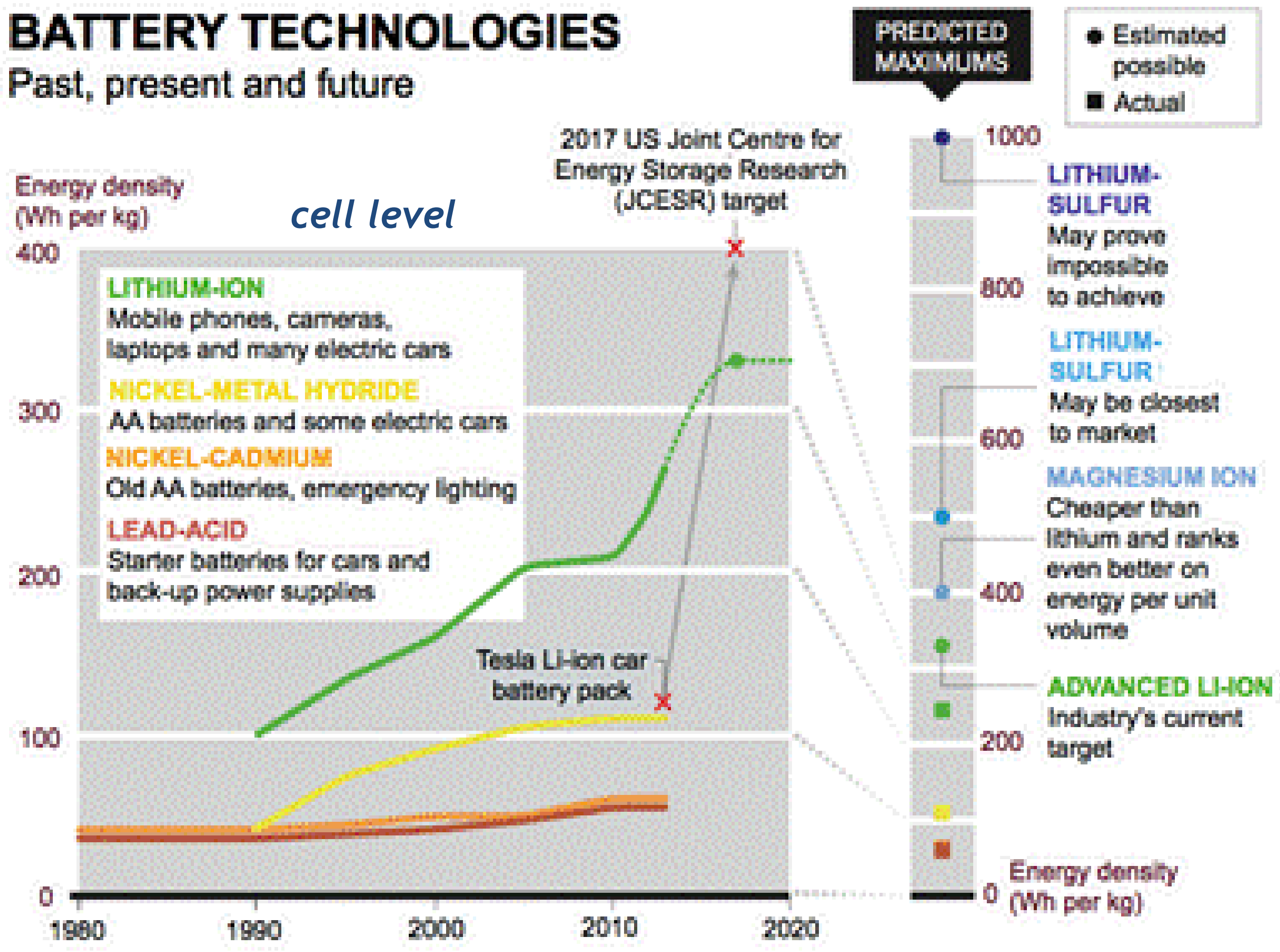
Alternative Energy Sources



Energy Source	Availability	Technical Maturity	Operational Considerations
Solar Power	Available globally; varies with location, season, weather, time	Widely deployed on the civil grid and military installations; limited deployment of tactical units	Small rugged panels can be beneficial; possible visible target; glint/glare concerns; requires cleaning
Wind Power	Available globally; varies with location, season, weather, time	Widely deployed on the civil grid and military installations; small units exist, but are typically not attractive for military use	While potentially beneficial, concerns with small wind turbines include reliability, visibility, and interference with communications
Hydrokinetic Power	Common but not everywhere; varies with location, season, weather, time	Utility-scale hydroelectric dams are mature and common; small portable tidal, wave, and micro-hydro power systems are under development	Requires sophisticated technologies and potentially a large material footprint; variable but more predictable than wind and solar
Geothermal Power	Exists in limited locations worldwide; where present, heat output is often steady	Very mature for civil applications	Requires considerable time and initial capital cost for construction; likely attractive for some enduring locations
Ocean Thermal Power	Exists in the deep sea and near specific islands	Under civil sector development and under evaluation for use on U.S. Kwajalein Army Base	Requires significant initial capital cost and large structures; may be attractive for some enduring locations

SOURCE: Anastasio, M., P. Kern, F. Bowman, J. Edmunds, G. Galloway, W. Madia, and W. Schneider. 2016. Task Force on Energy Systems for Forward/Remote Operating Bases. Government report. Defense Science Board. Under Secretary of Defense for Acquisition, Technology, and Logistics (USD(AT&L)). Available at https://dsb.cto.mil/reports/2010s/Energy_Systems_for_Forward_Remote_Operating_Bases.pdf. Accessed November 2020.

Potential Battery Improvements



cell level

BUT:

- Army-desired energy density at the **system level** of 300, 400, even 500 Wh per kg?? → *back to primary (non-rechargeable) batteries*

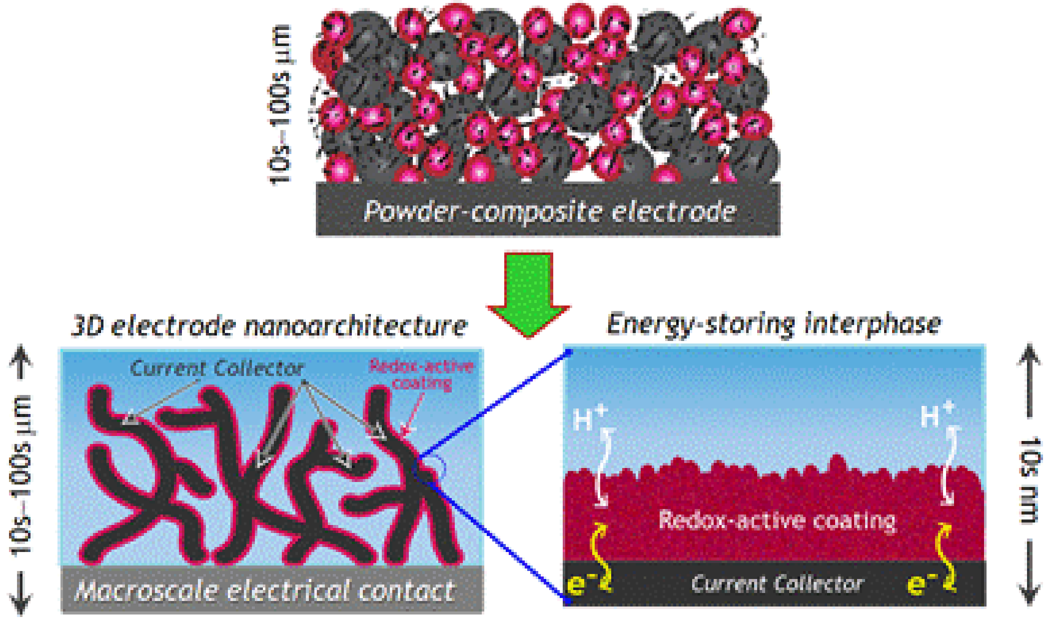
PLUS:

- Logistics issues affect transport of current rechargeable Li-ion batteries → *must now be shipped partially discharged*

SOURCE: Zu, C.-X. and H. Li. 2011. Thermodynamic analysis on energy densities of batteries. *Energy & Environmental Science* 4(8):2614–2624

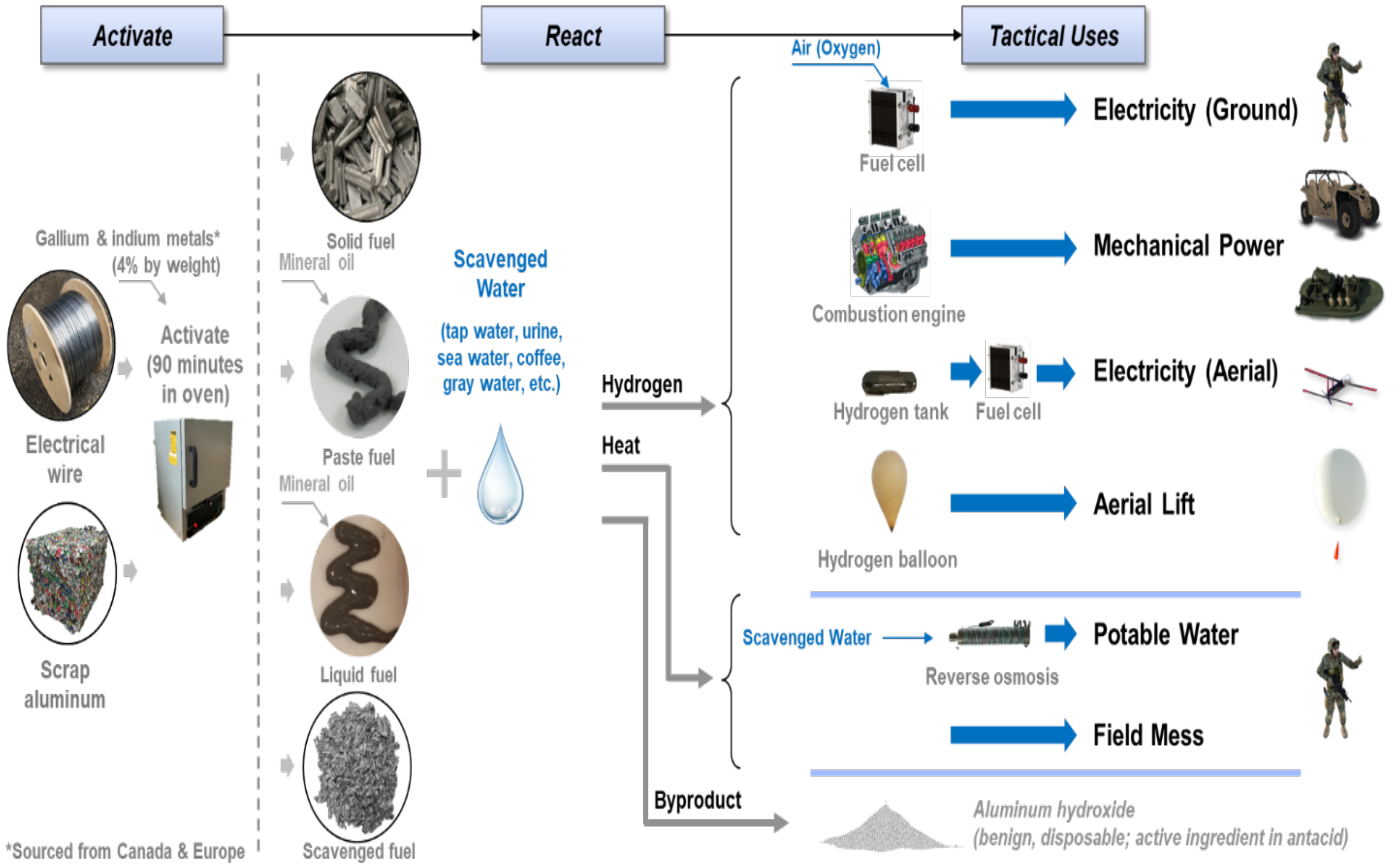
Battery Opportunities Feasible for 2035

- **Redesign electrode structures in today's Army-fielded batteries as 3D architectures**: Improved electronic wiring of the entire electrode volume better tolerates pulse-power demands and retains battery-effective energy density
- **Capitalize on advances in rechargeable aqueous zinc-based batteries using dendrite-suppressing zinc anodes**: Transform military-validated, safe primary batteries (MnO_2/Zn; Ni/Zn; Ag/Zn; Zn/air) into rechargeable, safe systems with lower balance-of-plant relative to proposed Li-based batteries



SOURCE: Long, J.W., Rolison, D.R., Sassin, M.B., Parker, J.F., Chervin, C.N., Palenik, M., Gunlycke, L.D., and So, C.R. 2020. Redefining charge-transfer interfaces for next-generation electrochemical power sources. *NRL* Memorandum Report NRL/MR/6170—20-10,149, U.S. Naval Research Laboratory, Washington, DC, September 2020

Hydrogen Produced From Aluminum Near Battlefield



Activate

React

Tactical Uses

Gallium & indium metals*
(4% by weight)

Electrical wire

Activate
(90 minutes in oven)

Scrap aluminum

*Sourced from Canada & Europe

Solid fuel

Mineral oil

Paste fuel

Mineral oil

Liquid fuel

Scavenged fuel

Scavenged Water

(tap water, urine, sea water, coffee, gray water, etc.)

+

Hydrogen

Heat

Byproduct

Air (Oxygen)

Fuel cell

Electricity (Ground)

Combustion engine

Mechanical Power

Hydrogen tank

Fuel cell

Electricity (Aerial)

Hydrogen balloon

Aerial Lift

Scavenged Water

Reverse osmosis

Potable Water

Field Mess

Aluminum hydroxide
(benign, disposable; active ingredient in antacid)

- Use of aluminum alloys to produce hydrogen when activated and combined with water is being studied including a prototype development project at General Atomics (initiated in November 2019) and independent work at MIT's Lincoln Laboratory.
- Further work on this technology should be focused on defining how the generated hydrogen might be used in a specific battlefield application, such as in proton-exchange membrane (PEM) fuel cell equipped reconnaissance vehicles where stealth mobility is essential.

War Gaming Recommendation

- Given the importance of power and energy on overall operational capabilities, the scope of future warfare computer simulations (i.e., tactical exercises without troops) should be expanded to include power and energy considerations.
- At a minimum, these simulations should include:
    - Identification of the quantity and form of energy to be transported
    - How much of this could be replaced with local sources
    - Where energy would be stored on or near the battlefield
    - Any set-up or take-down times
    - Redundancy and vulnerability concerns
    - At what rate (i.e., power) that energy could be released, and
    - Energy replenishment considerations, such as any refueling or recharging time requirements.
- These steps would ensure that the energy/power options being pursued by the Army are practical and realistic within their intended timeframe. These same steps were previously suggested by the Defense Science Board "Task Force on Survivable Logistics".

Decision/Trade-off Matrix

Givens and Musts

Use energy in a manner that provides the greatest net operational advantage on the battlefield
Supply whatever energy is needed to whomever and wherever they need it
Recognize growing power demand
Support enhanced battlefield situation awareness (improved communication, AI, edge computing)

	Wants									
Ground Combat Vehicles	Reduce transport requirements (fuel and batteries)	Reduce dismounted soldier weight burden	Reduce vehicle weight	Increase self-sustainment from 3 to 7 days	Provide rapid mobility	Maintain or reduce refuel/recharging times	Maintain or increase capability to disable seized sources	Employ environmentally friendly technologies	Reduce acoustic and thermal signature	**Other Considerations**
ICE/Transmission Efficiency Improvements	++		+	+	+	+			+	Up to 28% better fuel efficiency
Hybridization	++		-	+						10 to 20% fuel efficiency improvement
Diesel in lieu of JP8 (when in conflict)	+		+	+		+				9% higher volumetric efficiency
Biodiesel in lieu of JP8 (peacetime)								+		Carbon neutral/renewable fuel
Other Efficiency Improvements	+			+		+				5 to 8% fuel efficiency improvement
PEM Fuel Cell Hybrids using Hydrogen	--		-						++	4 to 7 times more supply trucks in convoy
Dismounted Soldier/Other Low Power Needs										
Solid Oxide Fuel Cells using JP8	+	+		+		+			++	Uses higher density JP8 ilo batteries
UGV "Mule" Vehicles (power export)	+	+		+	+	+				Uses machines to handle what they do best
Silent Soldier Power (Thermophotovoltaic)	+	+		+		+			-	Uses higher density JP8 ilo batteries
Forward Operating Bases										
Micro-Grid Technology (Multiple Sources)	+			+	+	+	+			Rapid set-up, integrates vehicle hybrid power
Micro-Grid Hybridization	+			+				+	+	Ensures operation at ICE FE "sweet spot"
Applicable to All										
Battery Energy Density Increases	+	+	+	+	+	+		+	+	Important for vehicles, soldiers, and FOB's

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Thank you for attending this Forum

Download the full report and highlights summary at:
http://nap.edu/26052