SAND2021-14581R

Design Guidelines for Deployable Wind Turbines for Military Operational Energy Applications

Brian Naughton, Sandia National Laboratories
Tony Jimenez, Robert Preus, and Brent Summerville, National Renewable Energy Laboratory
Brad Whipple, Dylan Reen, and Jake Gentle, Idaho National Laboratory
Eric Lang, University of Dayton Research Laboratory

November 2021

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

ACKNOWLEDGMENTS

The authors would like to thank the many reviewers of this document who provided their valuable time and extensive knowledge gained from years of wind industry and military experience to improve the information provided here. We aimed to capture and distill all that knowledge into a useful reference, but we also recognize that there are areas to improve and expand, and hope for a continued dialogue going forward.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

AC	alternating current
AHJ	authority having jurisdiction
AMMPS	Advanced Medium Mobile Power Source
ANSI	American National Standards Institute
ATP	Army Techniques Publication
AWEA	American Wind Energy Association
COTS	commercial off-the-shelf
D3T	Defense and Disaster Deployable Turbine
DARPS	Deployable Advanced Renewable Power System
DC	direct current
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DPGDS	Deployable Power Generation & Distribution System
D-REPS	Deployable–Renewable Energy Power System
E2S2	Expeditionary Energy & Sustainment Systems
FOB	forward operating base
GREENS	Ground Renewable Expeditionary Energy Network System
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IPDISE	Improved Power Distribution Illumination System Electrical
ISO	International Organization for Standardization
kW	kilowatt
LAMPS	Large Advanced Mobile Power Sources
MEMS	microgrid energy management system
MEPS	Mobile Electric Power Systems
MOS	military occupational specialty
NATO	North Atlantic Treaty Organization
NEC	National Electrical Code
SEPS	Small Expeditionary Power Systems
SPACES	Solar Portable Alternative Communications Energy System
SWT	small wind turbine
SWCC	Small Wind Certification Council
TMS	Tactical Microgrid Standard
TOP	Test Operating Procedure
TQG	Tactical Quiet Generator
USMC	United States Marine Corps

1. PURPOSE AND OVERVIEW

This document aims to provide guidance on the design and operation of deployable wind systems that provide maximum value to missions in defense and disaster relief. Common characteristics of these missions are shorter planning and execution time horizons and a global scope of potential locations. Compared to conventional wind turbine applications, defense and disaster response applications place a premium on rapid shipping and installation, short-duration operation (days to months), and quick teardown upon mission completion. Furthermore, defense and disaster response applications are less concerned with cost of energy than conventional wind turbine applications. These factors impart design drivers that depart from the features found in conventional distributed wind turbines, thus necessitating unique design guidance. The supporting information for this guidance comes from available relevant references, technical analyses, and input from industry and military stakeholders. This document is not intended to be a comprehensive, prescriptive design specification. This document is intended to serve as a written record of an ongoing discussion of stakeholders about the best currently available design guidance for deployable wind turbines to help facilitate the effective development and acquisition of technology solutions to support mission success.

The document is generally organized to provide high-level, focused guidance in the main body, with more extensive supporting details available in the referenced appendices. Section 2 begins with a brief qualitative description of the design guidelines being considered for the deployable wind turbines. Section 3 provides an overview of the characteristics of the mobile power systems commonly used in U.S. military missions. Section 4 covers current military and industry standards and specifications that are relevant to a deployable wind turbine design. Section 5 presents the deployable turbine design guidelines for the application cases.

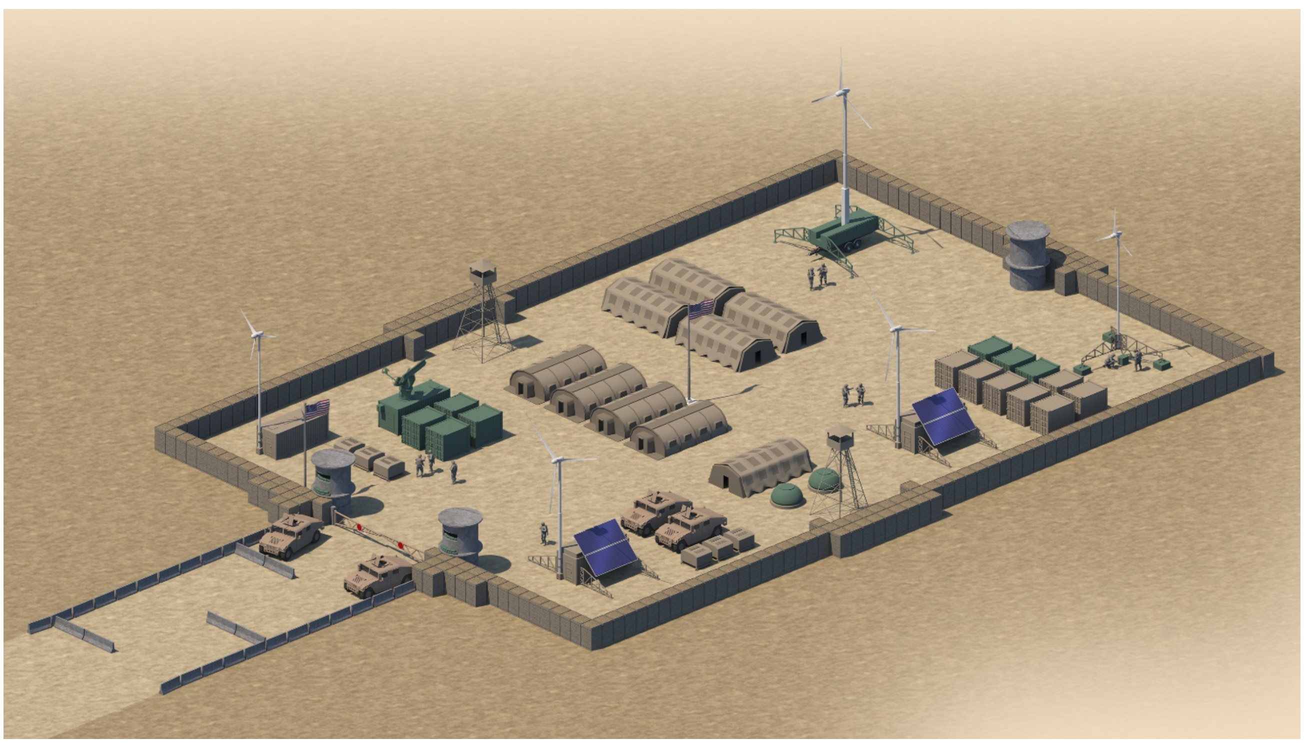

Figure 1. Rendering of various deployable wind turbine concepts at a forward operating base

2. DEPLOYABLE WIND APPLICATIONS

The report *Market Opportunities for Deployable Wind Systems for Defense and Disaster Response* [1] and a subsequent assessment of currently available commercial wind turbines identified three proposed size ranges for deployable wind systems to address three defense and disaster response applications with unique design requirements. One system is for individual or small teams, whereas the other two are for contingency bases of different scales. This structure was adopted for the design guidelines in this document with the general characteristics of each as follows:

Wind system for individual, small team, or small unmanned station

- Highly mobile, very quick setup and takedown (minutes)
- Lightweight, packable by person or small trailer
- Generally less than 3-kilowatt (kW) power
- Primary application is charging batteries and small electronics (DC)
- Installed and operated at the individual operator skill level with common tools

Wind system for contingency base (smaller)

- Support a portion of the loads of a company-sized element (~300 personnel) with deployments for weeks to months
- Setup and takedown in hours
- Physical dimensions and weight driven by organic logistics capabilities, common shipping containers
- Generally, single unit maximum rated power is 10–20 kW (estimated)
- Multiple units deployed and integrated into microgrid with other generation and storage
- Primary application is general operational loads using AC
- Installed and operated at the individual operator and unit skill level with common tools

Wind system for contingency base (larger)

- Support a portion of the loads of a battalion or brigade-sized (~1,000–3,000 personnel) element with deployments for months to more than a year
- Setup and takedown in hours to days
- Physical dimensions and weight driven by logistics capabilities, possibly including specialized equipment
- Generally, single unit maximum rated power is up to ~100 kW (estimated)
- Multiple units deployed and integrated into microgrid with other generation and storage
- Primary application is general operational loads using AC
- Installed and operated at the specialty/organizational skill level

3. OVERVIEW OF MILITARY MOBILE ELECTRIC POWER SYSTEMS

The development, procurement, and sustainment of mobile electric power systems for the U.S. military is primarily managed by the U.S. Army Office of the Project Manager Expeditionary Energy & Sustainment Systems (E2S2). The current structure of that office includes two subprograms for Small Expeditionary Power Systems (SEPS) and Mobile Electric Power Systems (MEPS). The building blocks of these mobile power systems are diesel generators ranging from 2 kW up to over 200 kW, generally providing spot power generation in a non-networked configuration. These program offices also continue to develop power system distribution and control products and alternative generation sources to augment the diesel spot generators. Other nonstandard and larger power generators are also used across the services.

3.1. Mobile Diesel Generators

The vast majority of military contingency operations rely on diesel-powered generators to provide electricity to mission-related loads. As a result, logistics capabilities and requirements, operator training and skills, and typical equipment for operational energy systems are primarily driven by these generators. This is an important consideration for designing a deployable wind system that is compatible not only technically, but logistically, with existing power generation systems.

Small Expeditionary Power Sources

The E2S2 Product Director Small Expeditionary Power Sources (PD SEPS) provides warfighters with expeditionary energy solutions that are less than 5 kilowatts. Current products are 2-kW and 3-kW tactical generators, with newer technologies currently in development to support platoon-scale power needs. There are also early-stage technical products to provide soldier-level power below 1 kW.

Advanced Medium Mobile Power Source

The Advanced Medium Mobile Power Source (AMMPS) line of generators from 5 kW to 60 kW are replacing the prior line of military Tactical Quiet Generators (TQGs), although both are currently in operation. AMMPS generators can be skid mounted, trailer mounted, or configured in a microgrid.

Large Diesel Power Systems

The largest mobile electric power systems start at 100 kW and generally include more advanced distribution systems to power larger bases. The Large Advanced Mobile Power Sources (LAMPS) generators are 100 kW and 200 kW in size. The Deployable Power Generation & Distribution System (DPGDS) is the largest mobile power system at 840 kW as a prime power unit (as compared to smaller tactical power units) to be used as part of a distribution system with transformers and lines to deliver power to loads.

3.2. Power Distribution and Control

The Improved Power Distribution Illumination System Electrical (IPDISE) system is an updated product that allows personnel to effectively distribute power between power generation and powered equipment while optimizing generator usage. The IPDISE system can network older generators and the newer LAMPS and AMMPS generators, facilitating operational fielded microgrids.

3.3. Mobile Hybrid Power Systems

The military has also developed mobile hybrid power system products to varying levels of maturity over the years, most of them not widely fielded for various reasons. Hybrid power systems include more than one generation or storage technology and may include diesel generators. A brief summary of a selection of these programs can be found in Appendix A, some of which have included alternative energy generators, including wind turbines. These programs can offer some insight into the benefits and shortcomings of prior hybrid designs.

4. MILITARY AND INDUSTRY REFERENCE STANDARDS AND SPECIFICATIONS

Existing military and industry standards and specifications, ranging from general to wind system-specific, provide useful and important foundational guidance applicable to deployable wind turbine systems. Brief summaries of the most relevant references are included in this section. Additional references to military and industry specifications and standards are included in the appendices.

4.1. Environmental Conditions

Military operations require reliable and rugged equipment to work in austere environments. The U.S. Department of Defense (DoD) has set forth standards and methods for testing equipment for a variety of global conditions. Although it may not be necessary to strictly adhere to these standards, it is important to recognize these standards do provide insight into the expectations of military equipment generally. When establishing the desired environmental operating range, it is important to consider the potential unintended design and performance consequences of requiring too wide of a range. Requirements for extreme weather or temperature operation can lead to expensive, heavy, complex solutions with degraded performance due to the added material or subsystems. In addition to the specific references covered in this section, the U.S. Army Test and Evaluation Command publishes Test Operations Procedures (TOPs) for a variety of equipment. Although there is not yet a specific TOP for wind turbines, there is one for photovoltaic systems, which is described along with other specific standards in Appendix F.

MIL-STD-810 Environmental Engineering Considerations and Laboratory Tests
The MIL-STD-810 standard addresses how products are tested for environmental survivability [2]. When products are marketed as "military grade" or "mil spec," they are often in reference to the products passing portions of the testing procedures outlined in MIL-STD-810. Currently, some solar panel products are marketed and sold as MIL-STD-810-approved. Revisions of this document are updated periodically and indicated with an incremental letter suffix. At the time of writing this document, the latest version is MIL-STD-810H dated 31 January 2019.

Section three of MIL-STD-810H describes the five "Climactic Design Types" that characterize the ambient environmental conditions that DoD equipment may encounter (Table 1). Note that the temperature range of transportation and storage is wider than the ambient conditions temperature range. These Climactic Design Types not only characterize the conditions under which equipment should function while installed, but also characterize the shipping and transport conditions. At a minimum, deployable turbines should be designed to function (or at least not suffer damage while not operating) in the Basic and Hot Climate Design Types. Combined, these two Climate Design Types define a temperature range of −32°C to +49°C of operational conditions. This temperature range is most comparable to the "Extreme Temperature Range" for wind turbines defined by the International Electrotechnical Commission (IEC) as at least −20°C to +50°C. This encompasses the vast majority of land surface areas in the world.

Beyond the items characterized in Table 1, both the IEC Standard and MIL-STD-810H discuss (in a qualitative sense) other environmental conditions, listed below, that may influence deployable turbine design:

- Temperature
- Humidity
- Air density
- Solar radiation
- Rain, hail, snow, and ice
- Chemically active substances
- Mechanically active particles (sand, dust)
- Lightning
- Earthquake
- Marine environment – corrosion.

Table 1. Summary of climatic conditions and daily cycles of temperature, solar radiation, and relative humidity from MIL-STD-810H.

		Operational Conditions				Storage and Transit Conditions			
		Ambient Air Temperature °C (°F)		Solar Radiation W/m² (Btu/ft²/hr)	Ambient Relative Humidity %RH	Induced Air Temperature °C (F)		Induced Relative Humidity %RH	Natural Environment Exposure Testing °C (F)
Climatic Design Type	Daily Cycle	Daily Low	Daily High			Daily Low	Daily High		
Hot	Hot Dry (A1)	32 (90)	49 (120)	0 to 1,120 (0 to 355)	8 to 3	33 (91)	71 (160)	7 to 1	32 to 49 (90 to 120)
	Hot Humid (B3)	31 (88)	41 (105)	0 to 1,080 (0 to 343)	88 to 59	33 (91)	71 (160)	80 to 14	Coastal Desert
Basic	Basic Hot (A2)	30 (86)	43 (110)	0 to 1,120 (0 to 355)	44 to 14	30 (86)	63 (145)	44 to 5	0 to 43 (32 to 110)
	Intermediate (A3)	28 (82)	39 (102)	0 to 1,020 (0 to 323)	78 to 43	28 (82)	58 (136)	See note[1]	
	Variable High Humidity (B2)	26 (78)	35 (95)	0 to 970 (0 to 307)	100 to 74	30 (86)	63 (145)	75 to 19	Humid Tropics
	Constant High Humidity (B1)	Nearly Constant 24 (75)		Negligible	95 to 100	Nearly Constant 27 (80)		95 to 100	
	Mild Cold (C0)	-19 (-2)	-6 (21)	Negligible	Tending toward saturation	-21 (-6)	-10 (14)	Tending toward saturation	0 to -32 (32 to -25)
	Basic Cold (C1)	-32 (-25)	-21 (-5)	Negligible	Tending toward saturation	-33 (-28)	-25 (-13)	Tending toward saturation	
Cold	Cold (C2)	-46 (-50)	-37 (-35)	Negligible	Tending toward saturation	-46 (-50)	-37 (-35)	Tending toward saturation	-32 to -46 (-26 to 50)
Severe Cold	Severe Cold (C3)	-51 (-60)		Negligible	Tending toward saturation	-51 (-60)		Tending toward saturation	< -46 (< -50)
Extreme Cold	Extreme Cold (C4)	-57 (-70)		Negligible	Tending toward saturation	-57 (-70)		Tending toward saturation	

[1] Relative humidity for the A3 storage condition vary too widely between different situations to be represented by a single set of conditions.

4.2. Transportation

The military has a variety of specifications covering logistical and safety considerations for the transportation of equipment. It is critical to consider all of the components of a deployable wind system when meeting transportation requirements. Items like batteries and permanent magnets have special restrictions due to their potential impact to safe operations.

Army Container Operations ATP 4-12 (May 2013)
Army Techniques Publication (ATP) 4-12, Container Operations [3], is the Army's doctrine for container management during operations and ensures that unit equipment and supplies are delivered in a timely and secure manner to the intended destination. To minimize intermodal logistics constraints, the Army uses standard 20-foot International Organization for Standardization (ISO) steel containers to move materiel. Although larger 40-foot ISO containers have been used in the past, DoD has removed them from their inventory to simplify handling equipment. Commercial 40-foot containers may be used to ship items to a primary logistics port, but the container-handling equipment at more forward operating locations is limited to the 20-foot containers.

Army Cargo Specialists' Handbook FM 55-17 (1999)
This Army field manual covers cargo handling specifications for intermodal transportation of material [4]. Part 4 of the manual discusses air transport on common cargo handlers like the C-17 and C-130 aircraft. These platforms use a standardized pallet system named the 463L. The 463L pallet dimensions are 108 inches by 88 inches by 2 1/4 inches. It weighs 337 pounds and has a total load capacity of 10,000 pounds, with a desired load capacity of 7,500 pounds.

Air Force Interservice Manual 24-204: Preparing Hazardous Materials for Military Air Shipments (July 2018)
This Air Force document has requirements for transportation and shipping of hazardous material, via military air shipment [5]. Specific to a wind turbine system may be the transportation of lithium batteries and magnetized materials. This document includes guidelines on the number of allowed lithium batteries, requirements on the segregation of lithium batteries, and other requirements. For magnetic components, any package that has a magnetic field strength of more than 0.00525 gauss measured at 4.5 m (15 ft) from any surface of the package is forbidden on military aircraft. Additional details on lithium batteries and magnetic materials from this specification can be found in Appendix F.

4.3. Electrical Power Systems and Components

A deployable wind turbine generator must comply with both military and industry standards to facilitate safe operation and interoperability with other power system components. Microgrids are an especially active area of development and implementation in commercial and military systems and the following standards are among the most prominent references.

Tactical Microgrid Standard
The Tactical Microgrid Standards Consortium is a DoD and industry collaborative working to develop a standard for military microgrids in contingency operations led by the U.S. Army Corps of Engineers. The standard will address interoperability requirements for microgrids and their components, including safety, protection and human factors, electrical interconnection, communications, controls, and cybersecurity. The standard is planned for public release in 2021. More details on the draft standard are provided in Appendix E.

IEEE 1547-2018 Standard for Interconnecting Distributed Resources with Electric Power Systems

The Institute of Electrical and Electronics Engineers (IEEE) 1547-2018 standard provides a uniform standard for interconnection of distributed resources with electric power systems. It provides requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection [6]. This standard is being adopted widely in commercial applications and the same functionality may be leveraged in a military context in the absence of a specific military specification such as the Tactical Microgrid Standard.

IEEE 2030 Standard for the Specification of Microgrid Controllers

A key element of microgrid operation is the microgrid energy management system (MEMS). It includes the control functions that define the microgrid as a system that can manage itself, operate autonomously or grid connected, and seamlessly connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services. The scope of the IEEE 2030 standard is to address the functions above the component control level associated with the proper operation of the MEMS that are common to all microgrids, regardless of topology, configuration, or jurisdiction [7].

National Electrical Code (NEC): Installation and equipment standards

The NEC is a standard for the safe installation of electrical wiring and equipment in the United States adopted by local states and municipalities and frequently referenced in DoD specifications. The local authority having jurisdiction (AHJ) inspects for compliance with these standards. Wind systems are installed to meet the NEC, the latest being NFPA 70: NEC 2020. The most relevant sections for wind energy are:

- 694 Wind Electric Systems
- 705 Interconnected Electric Power Production
- 706 Energy Storage Systems
- 710 Stand Alone Systems
- 712 Direct Current Microgrids

To pass inspection, the wind turbine electrical equipment, most notably the inverter, must have been tested to meet:

- IEEE 1547-2018 - IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
- UL 1741: Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources
- the communications requirements in IEEE 2030.5-2018 - IEEE Standard for Smart Energy Profile Application Protocol

4.4. Wind Turbines

IEC 61400-2, Part 2: Small wind turbines, Edition 3.0 the "IEC Standard," is the main worldwide standard for the design of small wind turbines. It is the basis for various national standards such as American National Standards Institute/American Wind Energy Association (ANSI/AWEA) SWT-1 (2016) AWEA Small Wind Turbine Standard, "AWEA Standard." Key related standards include: IEC 61400-11, Wind Turbines – Part 11: Acoustic Noise Measurement Techniques, IEC 61400-12-1, Wind Energy Generation Systems – Part 12-1: Power Performance Measurements of Electricity Producing

Wind Turbines, UL 6142: Standard for Safety for Small Wind Turbine Systems (2012), or for large turbines UL 6141: Wind Turbines Permitting Entry of Personnel.

The IEC definition of "small wind turbine" is a turbine with a rotor swept area of up to 200 m^2. This is comparable to a 50–60-kW rated wind turbine. This top-end rated power may be less for a deployable turbine because these turbines are likely to have an oversized rotor. Note that the U.S. Department of Energy (DOE) defines a small turbine as a turbine of up to 100-kW rated power.

Deployable turbines for "large base" applications may fall into the informal "medium turbine" category. The Small Wind Certification Council (SWCC) defines a medium turbine as one with a rotor swept area between 200 m^2 and 1,000 m^2. DOE defines medium turbines as having a rated power greater than 100 kW up to 1.0 MW. This category is informal because there are no separate design standards for turbines of this size range. Turbines in this size range are subject to the IEC 61400-1 standard for larger systems.

IEC 61400-2 provides a methodology for the design process, with an emphasis on the structural design, to give reasonable assurance that the turbine will survive and function during its specified lifetime (typically 20 years for commercial wind turbines). This begins with determining the environmental conditions under which the turbine is expected to operate. For some categories of conditions, such as wind regimes, the standard goes into some detail, characterizing four standard wind classes, I–IV, as well as making provision for designers to characterize a nonstandard "S-class" wind regime. For other conditions, such as dustiness, the discussion is much more qualitative, in essence stating that if the turbine is going to be deployed in some extreme environment, take care to design for that environment.

Once the environmental conditions are determined, the IEC Standard provides a process to calculate the structural design loads. The standard first has a general discussion of loads and load cases. It then provides three methodologies for determining the loads, simplified loads methodology, aeroelastic simulation modeling, and loads measurement. Once the loads are determined, the IEC Standard provides guidance on calculating stresses (with extensive discussion of safety factors) to reduce the chances of both fatigue failure and exceeding material strength limits.

The remainder of the IEC Standard includes discussions of protection, electrical system design, support structure, testing requirements, and documentation requirements. The appendices provide additional discussion on a variety of topics.

The focus of the ANSI/AWEA SWT-1 (2016) AWEA Small Wind Turbine (SWT) Standard is to provide accurate turbine information to consumers to enable apples-to-apples comparison. The AWEA Small Wind Turbine Standard incorporates IEC 61400-2 by reference and makes minor changes to the IEC Standard in the areas of testing, noise characterization, reporting, and labeling. It is in the process of being updated as of 2021.

Because IEC 61400-2 is the baseline for the SWT standard, the Defense and Disaster Deployable Turbine (D3T) team recommends focusing efforts on the IEC Standard. Appendix D provides recommendations for working within the IEC Standard and discusses potential minor deviations from the IEC Standard for deployable applications.

A key purpose of the IEC Standard is to provide reasonable assurance that the wind turbine can operate under the anticipated environmental conditions for the full design life. The design life is specified by the designer. For commercial turbines, a typical value is 20 years. For deployable turbines, a shorter design life may be appropriate. The IEC Standard does not mandate any particular design features. Any desired or mandated features will be part of the procurement specification, not the IEC Standard.

One important lesson learned from review of the IEC Standard is the importance of adequately characterizing the environment(s) under which deployable turbines will generally be expected to operate. This characterization is best done through consultation with multiple stakeholders and review of relevant existing industry and military specifications documents such as MIL-STD 810H. This environmental characterization should then feed into deployable turbine procurement specifications.

5. DEPLOYABLE WIND TURBINE DESIGN GUIDELINES

This section presents detailed design guidance on the life cycle of deployable wind systems for all applications mentioned in Section 2. Most of the information provided applies to all wind turbine designs; however, in a few specific sections, additional guidance is provided that pertains to airborne wind systems in particular. Airborne wind designs are a much less mature technology as compared to the more familiar tower-mounted wind turbine designs. Although airborne systems have some promising positive attributes, it is important to note that there are not yet well-established design, reliability, and performance standards for airborne systems as there are for more traditional wind turbine designs.

5.1. Mission Planning

Performance Modeling: The potential benefit of a deployable wind turbine to a particular mission can be assessed during the mission planning stage. The potential power production of a wind turbine requires, at a minimum, two pieces of information: the likely wind resource during the span of the mission and the power curve of the available wind turbine.

Wind Resource Information: Personnel will require access to wind resource data to estimate the power and energy production of the wind turbine in the mission area of interest. The most accurate wind resource data will be specific to a location, at the height of the wind turbine, and specific to the time of day and year of the mission. There are free and paid databases for this information globally, though high-quality validated data are lacking for much of the world, and the resulting uncertainty in estimated energy production should be anticipated. See Appendix C for more details.

- For individual/small team systems, referencing an average annual wind speed map nearest to the ground level is likely sufficient as the performance will likely be strongly influenced by the local topography during the short deployment. The resource will generally be less predictable and more turbulent at this height/scale.
- Bases with shorter missions (<1 year) should be aware of potential seasonal variations in wind resource.
- Already established or enduring bases may have or be able to acquire actual wind resource data at the site to improve performance estimates to guide decisions.
- For airborne wind systems, the operational height above ground is typically much higher than even the largest tower-mounted systems. In general, the wind resource increases with height to the top of the atmospheric boundary layer. In Figure 2, the wind resource at 200 meters, typical for an airborne wind system, is significantly higher than at 10 meters, where a typical deployable turbine might operate.

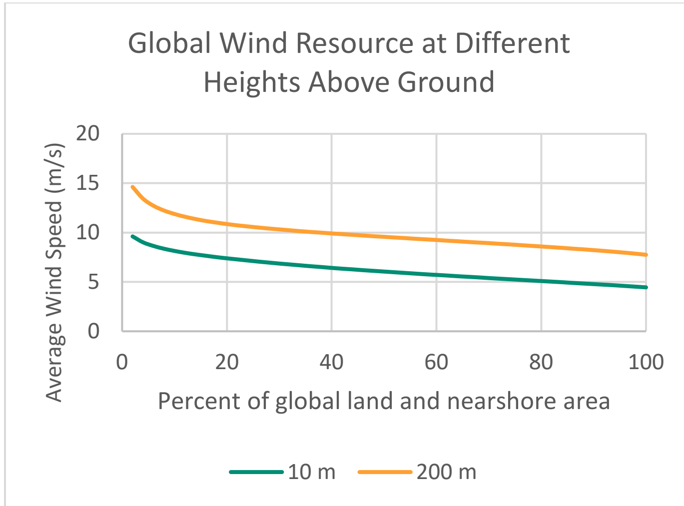

Figure 2. Average annual wind speed as a percent of global land and nearshore area, as well as height above ground

Wind Turbine Power Curve: A deployable wind turbine should be designed to operate in a wide range of wind speeds to maximize global deployment potential. Average global wind speeds at heights nearer to the ground (<50 m) tend to be much lower than those where commercial turbines are operating. It is important to consider very low wind-speed rotor designs that can extract more energy at lower wind speeds. Wind turbine power curves (power output as a function of wind speed) are part of the standard turbine technical documentation produced through a certification test. Figure 3 shows power curves for a hypothetical 15-kW turbine with two different rotor diameters. The blue curve represents a more standard rotor size, whereas the orange line represents a rotor that is 27% larger in diameter (61% more swept area). The power curve and the average wind speed are the primary inputs to calculate an expected annual energy production (AEP). The impacts of a larger rotor and the faster wind speed at increased height are summarized in Table 2. The method used to calculate the power curve and AEP in this example are provided in Appendix C.3.

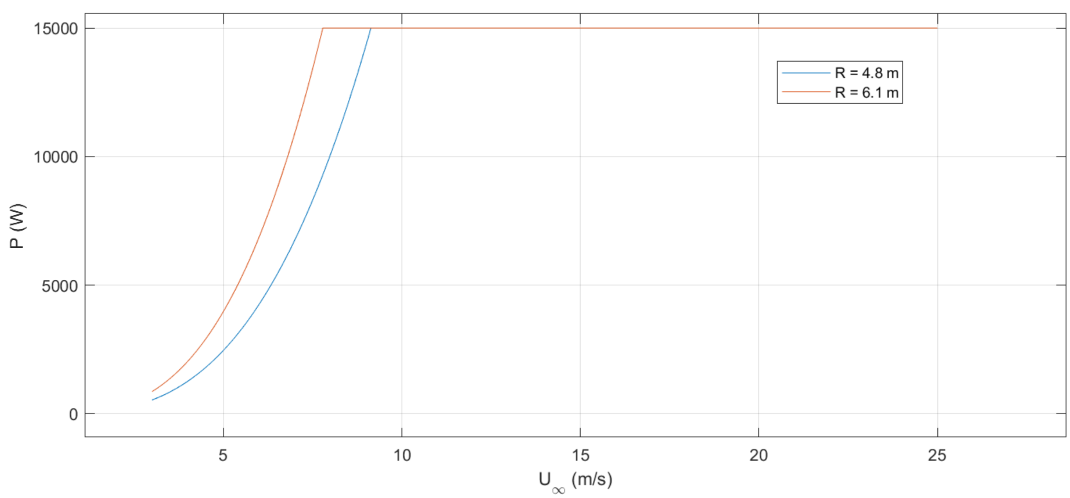

Figure 3. Example wind turbine power curves for two different rotor sizes

Table 2. Annual energy production of two different size rotors operating in two different average wind speeds corresponding to two different heights

	Average Wind Speed at 10 m (4.78 m/s)	Average Wind Speed at 200 m (8.22 m/s)
Rotor radius = 4.8 m	31,375 kWh	76,043 kWh
Rotor radius = 6.1 m	43,611 kWh	87,608 kWh

Mission Constraints: It is also important to consider the mission constraints regarding the potential deployment (siting) of a wind turbine. Requirements around electromagnetic, acoustic, and visual signatures, as well as physical obstruction with base operations both on the ground and in the air, may limit the deployment of a wind turbine. Special consideration should be given to airborne wind systems that have very long (200+ m) tethers that traverse the airspace in often complex patterns. Wind turbines may be able to mitigate these impacts through careful design and siting if sufficient specifications are provided during the design stage.

5.2. Transportation Logistics

The entire process of transportation from manufacturing location to contingency base should be considered in the design of a deployable wind turbine. Adhering to standard military shipping equipment and regulations will facilitate access to the most applications.

Cargo Formats: The largest container that is commonly transported to forward operating bases is a 20-foot ISO steel shipping container. Larger containers require specialized handling equipment that is not common in typical unit equipment inventory. For air transport, cargo handling aircraft typically require equipment to be loaded onto 463L pallets. Details on military logistics requirements can be found in Appendix F.1.

Hazardous Materials: There are important restrictions on materials considered to be hazardous. For wind turbines, the primary concerns are likely to be magnetic materials and battery materials like lithium. Details can be found in Appendix F.1.

Logistics Burden: It is important to consider the logistics burden of a deployable turbine design relative to alternatives such as diesel generators plus fuel. The wind turbine should typically be deployed long enough to produce at least as much energy as a similar container loaded with a diesel generator and fuel. For individual or small team-portable wind turbines, the trade-off is more likely to be non-rechargeable battery weight and space compared to the wind turbine weight and space. Small trailers hauled by an ATV may also be viable for this application size. The U.S. Marine Corps Deputy Commandant for Combat Development and Integration sets requirements for what a warfighter can lift and carry for different missions. In general, the deployable turbine needs to more than make up for its own logistical burden by displacing fuel or batteries.

5.3. Installation and Removal

Siting: Proper siting of the deployable turbine for installation is very important to achieve the best performance and minimize conflicts with the mission and impacts of local topology and obstructions. Guidance on local siting considerations for performance can be found in Appendix C.2. Mitigating potential conflicts with base activities will be mission-specific, but having clear documentation on the wind turbine physical and signature characteristics would help facilitate effective on-site placements.

Foundation: It is preferred and sometimes required that the deployable turbine foundation cannot significantly disturb the local ground surface, such as with a poured concrete foundation. Preferred configurations would be placed on the ground with ballast or deployable outriggers. In some instances, it may be allowable to have a foundation that could be set in a hole and backfilled (no concrete) or based on helical piles that can be screwed in and removed when decommissioning, assuming the equipment to do so was readily available. Simple leveling capabilities should be designed into the system, and perhaps some additional tolerance for being out of plumb. Detailed foundation considerations for deployable turbines can be found in Appendix B.

Tower: There is a trade-off between a taller tower (for increased energy production) and a shorter tower (for ease of installation and shipping and reduced visual signature and airspace conflict). The rotor should be higher than nearby vegetation and structures to avoid a significant reduction in energy production (see Appendix C.2). The design choice between guyed and free-standing towers should consider time and complexity of setup, physical footprint, and obstructions with mission activities. Structural weight may be a bigger driver than cost or a long design life, especially for the human-portable systems. Lightweight materials like aluminum and glass or carbon fiber composites may be viable design choices. Time to erect and lower is critical for human-portable systems, but also a consideration for storm survival of systems installed at bases, especially those that have rotors optimized for low wind speeds.

Airborne wind generators have some unique benefits such as not requiring a tower and the ability to reach more consistent and higher wind speeds hundreds of feet off the ground. However, these systems have moving tethers, sometimes carrying electrical power, that are also hundreds of feet long that must be considered as part of the airspace use and potential conflict.

Assembly: In general, the deployable wind system should be assembled with minimal personnel, training, tools, and time. Soldiers should ideally be capable of setting up the wind turbine system with the typical equipment of their unit without special training beyond what might be required to set up a diesel generator, for example. If nonstandard tools are unavoidable, they should be supplied with the turbine with backups, and if at all possible be commercial off-the-shelf (COTS) for ease of replacement. Individual components should not be too heavy or awkward for soldiers to handle. For the turbine at a larger base, installation support may be provided from a military occupational specialty (MOS) such as an Interior Electrician (12R, 1141) or a Tactical Power Generation Specialist (91D, 1142), along with more specialized equipment, or a contractor. The soldier training guide for the Tactical Power Generation Specialist (91D) is a good reference for the skills and tasks typical for this MOS [8].

5.4. Operations and Maintenance

Operations: The deployable turbine should be as easy and intuitive to operate as mobile diesel generators. Safety systems should be incorporated into the design or operation of the turbines to mitigate the damage of harsh conditions such as extreme winds or icing. It may be beneficial to include special operating modes that support mission requirements such as reduced acoustic, visual, or electromagnetic signatures.

Maintenance: The deployable wind turbine should require minimal maintenance while deployed but can likely be inspected more frequently than typical commercial systems. A good basis for reference would be the maintenance requirements for the AMMPS diesel generators. System faults should be easy to diagnose and repair with supplied parts and tools, preferably COTS tools to facilitate ease of sourcing. It may be possible to have more specialized maintenance between deployments.

5.5. Power System Integration

Unlike diesel spot generators, a deployable wind turbine will not be directly connected to a load unless the load is a rechargeable battery as in the case of the human-portable system. The deployable wind turbine should be designed to integrate into hybrid power systems to include, at a minimum, a battery storage device, but also likely diesel generators and solar photovoltaics. These could be incorporated as part of an integrated power system (see Appendix G for examples) or as part of a distributed microgrid with some sort of control system. Currently, the DoD has a draft Tactical Microgrid Standard (TMS) (more details in Appendix E), but the TMS needs further development to account for the non-dispatchable nature of wind energy production. A microgrid standard is also lacking on the industry side, though both the IEC and UL (UL3001) are working on microgrid standards. Until a DoD standard is in place, deployable turbines should be designed to meet IEEE 1547-2018 and (when they are released) the IEC and UL microgrid standards. Another important design consideration for hybrid microgrid power systems is the energy management strategy. The choice of using dispatchable diesel power vs. non-dispatchable renewable power and also battery charge and discharge timing can all have significant impacts on component life, efficiency, and overall fuel savings. This is an active area of research and development broadly.

5.6. Institutional Considerations

Beyond the technical considerations discussed in the prior sections, a further important consideration in the successful deployment of wind technology to support military operations is the institutional characteristics of the Department of Defense or other end use customers, governments, and agencies. Moving from short-lived, one-off technology solutions to a longer-term Program of Record requires ongoing engagement with various personnel from soldiers in the field to senior military leadership. The more successful designs will be simple to understand, operate with minimal or no training, and provide a tangible benefit to the mission.

APPENDIX A. CONTAINER ANALYSIS

An analysis was performed of the maximum size turbine that can be transported in standard 20-ft and 40-ft ISO shipping containers. Table 3 lists container dimensions.

Table 3. Standard shipping container dimensions [9]

	Exterior			Interior			Door Opening		Tare Weight
	Length	Width	Height	Length	Width	Height	Width	Height	
20-ft Standard Container	20 ft (6.1 m)	8 ft (2.4 m)	8 ft 6 in. (2.6 m)	19 ft 3 in. (5.9 m)	7 ft 8 in. (2.3 m)	7 ft 9 7/8 in. (2.4 m)	7 ft 8 in. (2.3 m)	7 ft 5 in. (2.3 m)	5,050 lbs. (2,290 kg)
40-ft Standard Container	40 ft (12.2 m)	8 ft (2.4 m)	8 ft 6 in. (2.6 m)	39 ft 5 in. (12.0 m)	7 ft 8 in. (2.3 m)	7 ft 9 7/8 in. (2.4 m)	7 ft 8 in. (2.3 m)	7 ft. 5 in. (2.3 m)	8,000 lbs. (3,629 kg)

Assumptions

Turbine system components to be transported in the container include blades, tower, nacelle, foundation base (analyzed in Appendix B), inverter, and controls. Although larger turbines may require multiple containers for transport, it is preferred to have a complete turbine system in a single container. The assumed turbine archetype for this analysis is a horizontal axis wind turbine.

Blades

A horizontal axis wind turbine will typically have three blades. Blade length is important as energy capture is proportional to the square of the rotor radius. For this analysis, the maximum blade length is assumed equal to the interior length of the container. There are three ways to gain extra blade length: blades can be segmented, blades can be placed corner-to-corner in the container, or rotor diameter can be increased using hub extenders. Segmented blades and hypotenuse placement are assumed to be impractical at this time, but the use of hub extenders will be further examined.

Figure 4. Northern Power Systems NPS 100C-24 with hub extenders (en.wind-turbine-models.com)

Hub extenders, shown in Figure 4, are occasionally used in the industry to increase rotor diameter, and thus energy capture, without increasing blade length. Based on past and current hub extender use, this analysis assumes a maximum increase in rotor diameter of 14%, which will increase rotor swept area by 31%.

Maximum Rotor Size

Table 4 shows the maximum rotor radius, rotor diameter, and rotor swept area for the 20-ft and 40-ft container for both the baseline assumption of no hub extenders (blade length is equal to rotor radius) and with hub extenders (assuming a maximum increase in rotor radius of 14%).

Table 4. Maximum rotor size per container

Container	Max rotor radius	Max rotor diameter	Max rotor swept area
20 ft (no hub extenders)	5.87 m (19.3 ft)	11.7 m (38.5 ft)	108 m^2 (1,164.2 ft^2)
20 ft with hub extenders	6.69 m (22 ft)	13.4 m (43.9 ft)	141 m^2 (1512 (1,512.9 ft^2)
40 ft baseline	12.0 m (39.4 ft)	24.0 m (78.8 ft)	454 m^2 (4,881 ft^2)
40 ft (no hub extenders)	13.7 m (44.9 ft)	27.4 m (89.9 ft)	589 m^2 (6,343.4 ft^2)

Maximum Turbine Power

Figure 5 shows the rotor swept areas and rated power of a variety of small wind turbines currently on the market. The yellow shaded region represents the range of rated power for a given swept area. The general industrywide trend is toward low specific power (rated power measured in watts per square meters of swept area); rotor size is increasing for a given rated power, thus increasing energy capture in lower wind speed regimes. For the 20-ft container, the rated power of the maximum rotor size could range from the 11-kW Gaia turbine with its 13-m (42.7-ft) rotor to the 30-kW Bestwind with a 13.1-m (43-ft) rotor. For the 40-ft container, the rated power of the maximum rotor size could range from about 80 kW to 125 kW, but with fewer models in this range, a maximum rated power of 100 kW is a reasonable assumption.

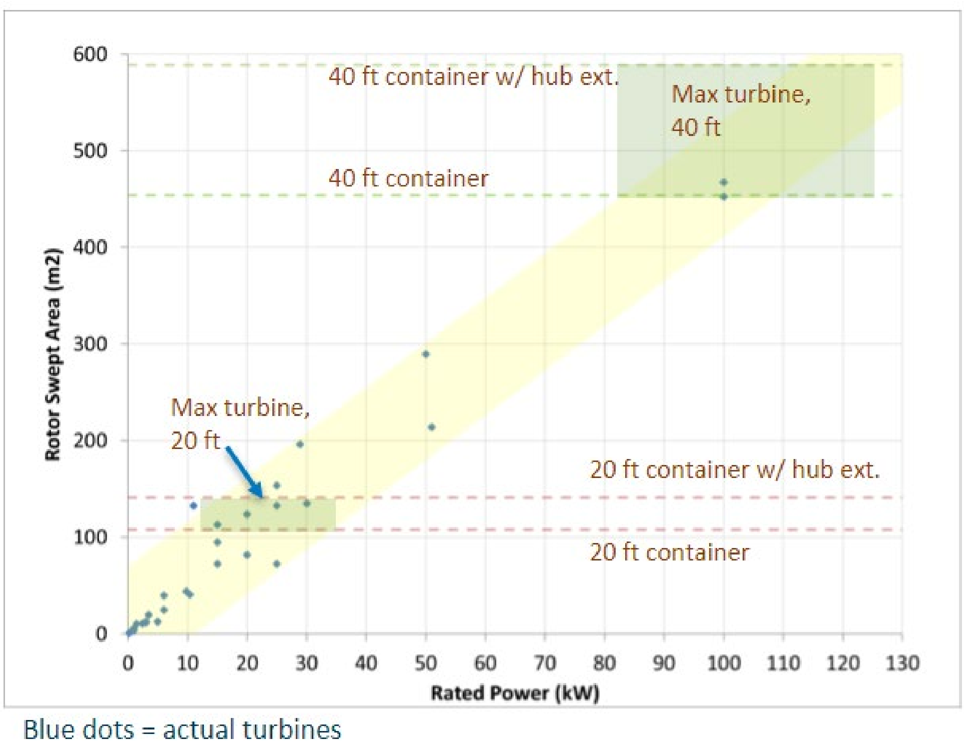

Figure 5. Rated power versus rotor swept area

Tower Height

As shown in Figure 6, towers are typically either monopole (no guy wires), guyed towers, or perhaps telescoping for deployable turbines. They can be a single piece or segmented. This analysis assumes the maximum tower segment length is equal to the interior length of the container.

Figure 6. Single-piece, monopole tower (left, Pika Energy turbine, NREL PIX 31470), segmented, guyed tower (center, Bergey Windpower turbine, NREL PIX 16742), and telescoping tower (Uprise Energy turbine, Idaho National Lab)

The maximum tower height for each container size is presented in Table 5. For the 20-ft container, the maximum tower height ranges from 5.9 m (19.3 ft) for one segment to 29.3 m (96.3 ft) for five segments. For the 40-ft container, the maximum tower height ranges from 12.0 m (39.4 ft) for one segment to 36.0 m (118.3 ft) for three segments. Although more tower segments could fit into the container, a maximum tower height of approximately 30 m (~100 ft) was assumed for a deployable system. The tower will require a foundation, which is analyzed in Appendix B.

Table 5. Maximum tower height options per container

Max Tower Height 20-ft Container		Max Tower Height 40-ft Container	
5.87 m (19.3 ft)	1 segment	12.0 m (39.4 ft)	1 segment
11.7 m (38.5 ft)	2 segments	24.0 m (78.8 ft)	2 segments
17.6 m (57.8 ft)	3 segments	36.0 m (118.3 ft)	3 segments
23.5 m (77.0 ft)	4 segments		
29.3 m (96.3 ft)	5 segments		

Nacelle

The nacelle includes the hub (connects blades to shaft), generator, braking system, pitching system, yaw system, gearbox, and any up-tower power electronics. The hub is sometimes a separate component, especially for larger turbines. The weight and size of the nacelle increases with turbine size and must be accounted for in the container. For example, the nacelle for the 10-kW Bergey Excel 10 weighs 444.5 kg (980 lbs.), whereas the nacelle for the 100-kW NPS 100-C weighs 6,291 kg (13,869 lbs.)

Inverter, Controls, Battery
The power electronics and battery energy storage systems are important components in the wind turbine system. These components will typically be mounted in or on the container and thus must be accounted for. For example, the new Intergrid IG25 inverter, used in turbines up to about 25-kW rated power, weighs 39 kg (85 lbs.). Battery systems can add significant weight to the system; for example, the 15-kWh RELiON lithium iron phosphate weighs 176 kg (388 lbs.).

Examples of Containerized Systems
Figure 7 shows the wind + solar + storage "hybrid cube" system from HCI Energy that transports in a 20-ft shipping container. The wind turbine is the Skystream 3.7 with 2.4-kW rated power, 3.72-m (12.2-ft) rotor diameter, and 10.9-m^2 (117-ft^2) rotor swept area. The total system weight is 18,000–22,000 lbs. (8,166–9,979 kg), depending on the options selected. The two-segment, 40'-ft tower transports on the container top and is tilted up onsite using a gin pole.

Figure 6 shows the telescoping tower from Uprise Energy. Figure 8 shows the system transformed into a portable trailer that fits within a standard 20-ft container for transport. The trailer, which serves as the turbine foundation, contains the 10-kW turbine with its five 3.4-m (11.1-ft) blades, providing 37.4-m^2 (403-ft^2) rotor swept area, the 14.5-m (47.6-ft) telescoping tower, inverter, and batteries. The total system weighs 5,443 kg (12,000 lbs.).

Figure 7. HCI Energy hybrid cube

Figure 8. Uprise Energy system in trailer mode (photo from Idaho National Lab)

Figure 9 shows the Deployable Advanced Renewable Power System (DARPS) under development by Bergey Windpower. This system transports as a 40-ft container (not inside a container) and is made stackable with other 40-ft containers. Bergey utilizes two of their Excel 15 turbines on 11.6-m (38-ft) tilting monopole towers along with batteries and microgrid power electronics. The total system weight is 8,849 kg (19,509 lbs.).

Figure 10 shows the 100-kW turbine from Northern Power Systems being deployed on Necker Island. The complete system, including the turbine, 24-m (79-ft) diameter rotor, 20-m (66-ft) tilting monopole tower, and ballasted foundation, ships in three 40-ft containers and can be installed in 1 week with a 3–4-person crew using an excavator and telehandler.

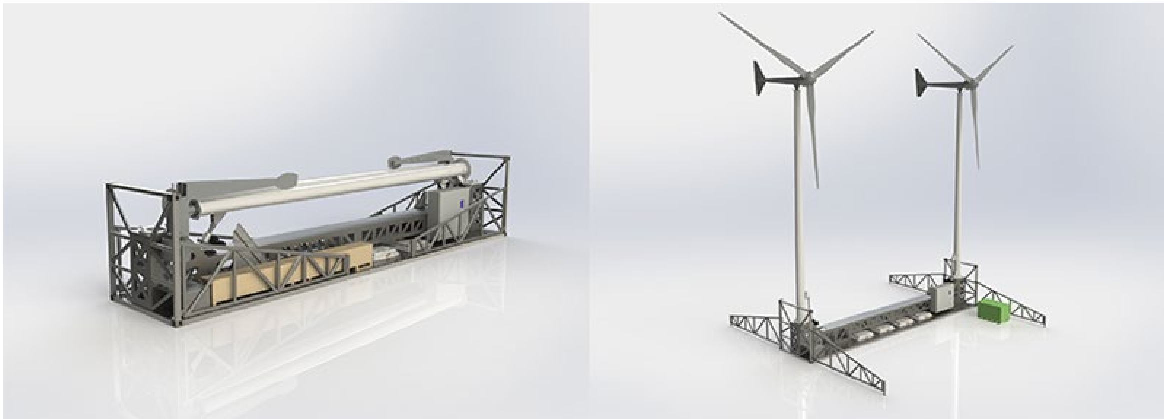

Figure 9. DARPS system from Bergey Windpower

Figure 10. NPS 100-24 deployed on Necker Island

Summary

A standard 20-ft ISO container can transport a deployable wind turbine system with a maximum rotor diameter of 11.7 m (38.4 ft) to 13.4 m (44 ft), depending on the use of hub extenders. This translates to a maximum turbine size of about 11 kW to 30 kW on a tower from 5.9 m (19.4 ft) to 29.3 m (96.1 ft) in height. A standard 40-ft ISO container can transport a deployable wind turbine system with a maximum rotor diameter of 24 m (78.7 ft) to 27.4 m (89.9 ft), depending on the use of hub extenders. This translates to a maximum turbine size of about 80 kW to 125 kW on a tower from 12 m (39.4 ft) to 36 m (118.1 ft) in height.

This analysis assumes that blade length determines the maximum turbine size per container, but total system weight and material handling requirements are also significant design drivers. Due to limitations of available material handling equipment, system weight may be more of a constraint than rotor size.

Container layout depends on how a turbine is installed. For more traditional, long-term distributed wind installations, the turbine system is typically broken down into components and efficiently packed into a container for shipping, thus requiring extensive installation time and effort. For deployable wind systems, innovation is required to maximize ease of installation (time, skill level, installation equipment).

APPENDIX B. FOUNDATION ANALYSIS

This study considers the stability of non-permanent foundation options for deployable wind turbines packaged into 20-ft and 40-ft shipping containers as foundations, as well as trailer-mounted systems that fit into a 20-ft shipping container.

Assumptions

Appendix C examines the issue of which extreme wind speed assumption is best suited for deployable wind systems. This analysis explores the 1- and 50-year extreme winds, as well as the TIA-222 extreme wind speed of 50 m/s (112 mph). The IEC extreme winds are discussed in Appendix D. ANSI/TIA-222: Structural Standard for Antenna Supporting Structures, Antennas and Small Wind Turbine Support Structures, is a Telecommunications Industry Association (TIA) standard commonly used by tower designers for small, distributed wind systems. The analysis assumes the turbine has reached cut-out in these extreme winds and the rotor is parked. Overturning moments from extreme winds are modeled per the simplified load methodology in IEC 61400-2 edition 3. A minimum factor of safety of 1.5 is assumed (i.e., the resistance to the overturning moment should be at least 1.5 times the extreme wind overturning moment).

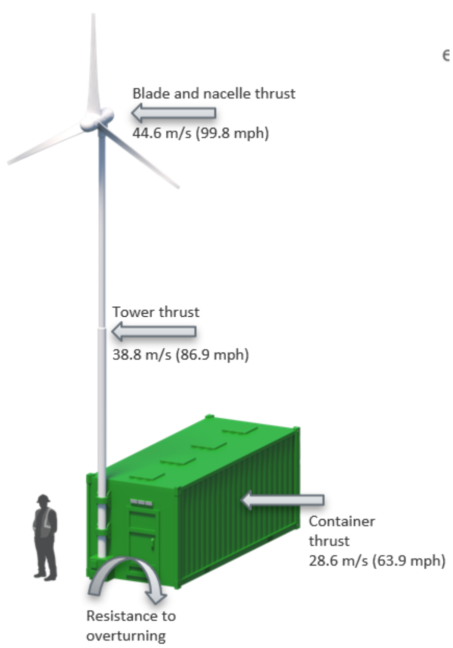

Figure 11. Overturning moments and resistance to overturning

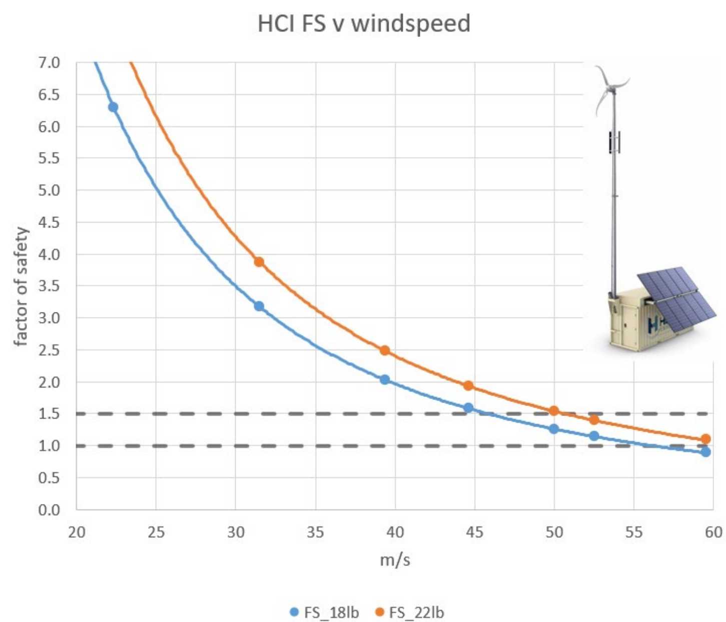

Figure 12. HCI Hybrid Cube analysis

Modeling

Modeling was performed on three deployable turbines systems and then a generic model was developed to inform foundation guidelines for a range of turbine sizes. Load case H of the simplified loads methodology (SLM) in the IEC61400–2 standard, Extreme Wind Loading, was used to calculated thrust loads and overturning moments. As shown in Figure 11, thrust loads on the rotor blades and nacelle result in an overturning moment with a moment arm equal to the turbine hub height. Tower thrust loads assume a moment arm of half the hub height. Thrust loading on the container side is significant, but the assumed moment arm is only half the container height. Hub height wind speeds were sheared down to half the hub height for the tower moment and half the container height for the container moment assuming a wind shear exponent, alpha, of 0.2. The system will resist overturning with a counteracting moment of the total system weight times a moment arm of half the container width.

HCI Hybrid Cube Analysis

The Hybrid Cube from HCI Energy utilizes a Skystream wind turbine on a 12.2-m (40-ft) segmented tilting monopole mounted to the corner of the 20-ft container. Shown in Figure 12, assuming a reported total system weight of 18,000 lbs. (8,165 kg) to 22,000 lbs. (9,979 kg), depending on system options, the Hybrid Cube, which is not equipped with outriggers, will resist overturning up to the 1-year extreme wind for IEC class II, 44.7 m/s (100 mph), with a total system weight of 18,000 lbs., or the Telecommunications Industry Association extreme wind, 50 m/s (112 mph), with a total weight of 22,000 lbs.

Uprise Energy Analysis

Shown in Figure 13, analysis of the trailer-mounted 10-kW deployable turbine system from Uprise Energy, equipped with outriggers, shows that the system will resist overturning up to the 1-year extreme for IEC class III, 39.4 m/s (88 mph) at a system weight of 8,000 lbs., or up to 47.8 m/s (107 mph) at a 12,000-lb. (5,443-kg) system weight containing onboard batteries. Calculations performed by Uprise, shown in blue, agree with the calculations from the National Renewable Energy Laboratory.

Bergey Windpower Deployable Advanced Renewable Power System (DARPS) Analysis

Shown in Figure 14, analysis of the DARPS from Bergey Windpower, which features outriggers and is spatially equivalent to a 40-ft shipping container, shows that the system will resist overturning up to the 50-year extreme for IEC class II, 59.5 m/s (133 mph) at a system weight of nearly 20,000 lbs. (9,072 kg). Calculations performed by Bergey Windpower largely agree with the calculations from the National Renewable Energy Laboratory.

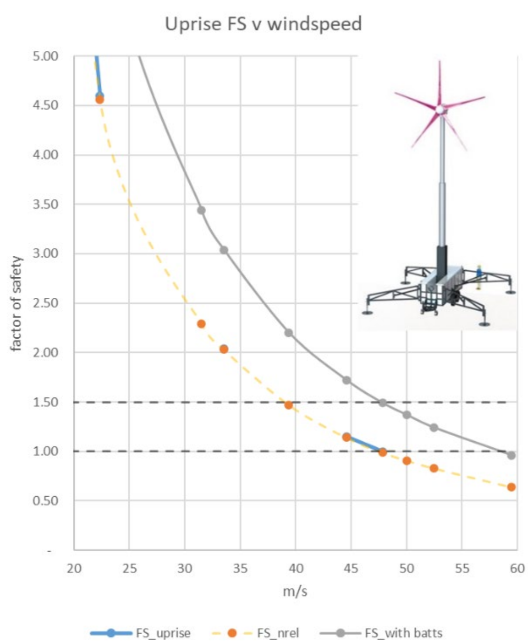

Figure 13. Uprise Energy analysis

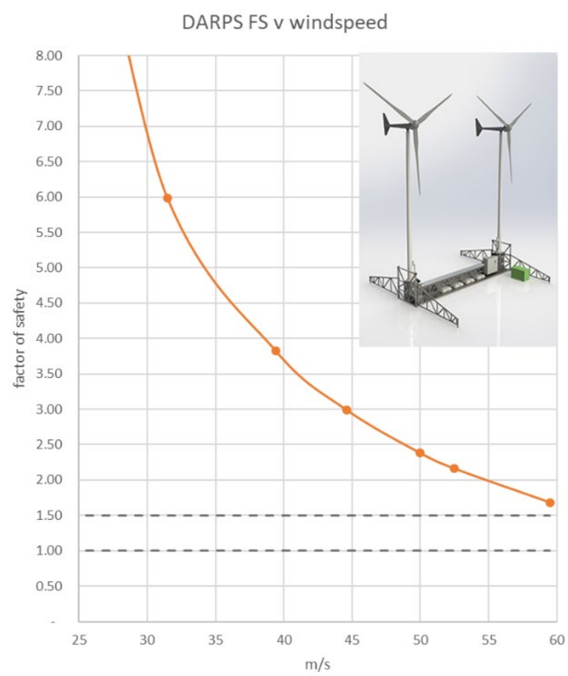

Figure 14. Bergey Windpower analysis

Generic Model

With confidence in the calculations and methodology, a generic model was developed to study foundations for the full range of turbine sizes that will fit into 20-ft and 40-ft shipping containers (from the Container Analysis). As shown in the example in Figure 15, projected areas of turbine blades, nacelles, and tower were collected, and curves were fit to the known data points. The total system weight assumption of 3.5 times the empty container weight was derived from the HCI Energy and Uprise system weights, resulting in assumed total weights of 17,739 lbs. (8,046 kg) for 20-ft container systems and 28,101 lbs. (12,746 kg) for 40-ft container systems. The extreme wind speed was assumed to be the 1-year extreme wind for IEC class II conditions or 44.6 m/s (100 mph). The 1.5 factor of safety for resistance to overturning remains. For 20-ft containers, a nominal hub height of 12.2 m (40 ft) was assumed (two 20-ft segments). For 40-ft containers, an 18.3-m (60-ft) hub height was assumed to provide adequate rotor ground clearance for the larger turbines. The drag coefficient for the blades and nacelle is assumed to be 1.5, and 0.7 for the tower, per IEC 61400-2. If outriggers are required, their length is assumed to be half the container length (e.g., 10 ft (3 m) for a 20-ft container.)

Aproj, blade (m^2) from
Air Breeze
Skystream
Kestrel e400
Proven P11
Uprise
Excel 10
Excel 15
QED PHX
Eocylce 25
NPS 100C-21
NPS 100C-24
NPS 100C-27
NPS 100C-28

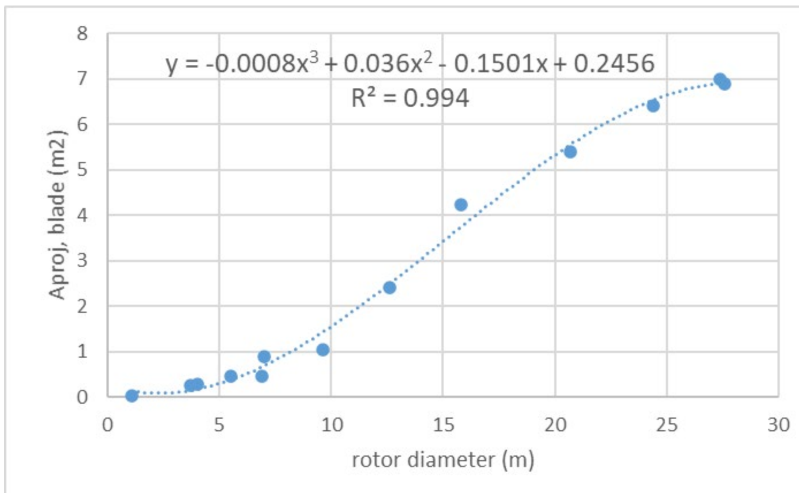

Figure 15. Projected blade area versus rotor diameter

Maximum Capabilities per Foundation Type

Figure 16 shows the foundation options explored in this analysis. The capabilities of each option are described below. As a general caveat, the commercial wind turbine examples provided below for reference are generally not configured for a deployable operation.

20-ft container with no outriggers

A 20-ft container with no outriggers was found to serve as a sufficient foundation for a turbine with a rotor diameter up to 5.4 m (17.7 ft), or two turbines with rotor diameters of 3.5 m (11.5 ft). For example, the 3-kW Sonsight Wind SS3 has a rotor diameter of 5.0 m (16.4 ft).

20-ft container with outriggers

For rotor diameters greater than 5.4 m (17.7 ft), outriggers are required to prevent overturning up to a rotor diameter of 11.9 m (39 ft) or up to the maximum turbine that will fit into a 20-ft container. At a maximum 13.4-m (44-ft) rotor diameter (utilizing hub extenders), earth anchors are required on the end of each outrigger. Examples of turbines in the max range include the 20-kW QED PHX 20 with a 12.6-m (41.3-ft) rotor diameter or the 30-kW Bestwatt 30 with a 13.1-m (43-ft) rotor diameter.

20-ft trailer with outriggers
For trailer-mounted systems that transport in a 20-ft shipping container, the thrust force on the trailer is slightly lower than a container, and with outriggers this system can support a turbine with a rotor diameter up to 12 m (39 ft). For example, the 15-kW EAZ 12 has a 12-m (39.4-ft) rotor diameter.

40-ft container with outriggers
Larger turbines have longer blades, and thus require a 40-ft shipping container for transport and foundation. A 40-ft container with outriggers will resist overturning in 44.7-m/s (100-mph) winds for a rotor diameter up to 17.4 m (57 ft) or up to the maximum size that will fit into a 40-ft container, or 27.4-m (90-ft) rotor diameter if earth anchors are added to the outriggers. As an example, the NPS 100 has a range of rotor diameters from 21 m (69 ft) to 27 m (88.6 ft).

Independent, ballasted system
Ballasted foundations, such as offered by ARE Telecom, can also be an option for a deployable wind turbine. Many options exist, and it is recommended that the foundation and tower be engineered for the specified wind turbine and balance of system.

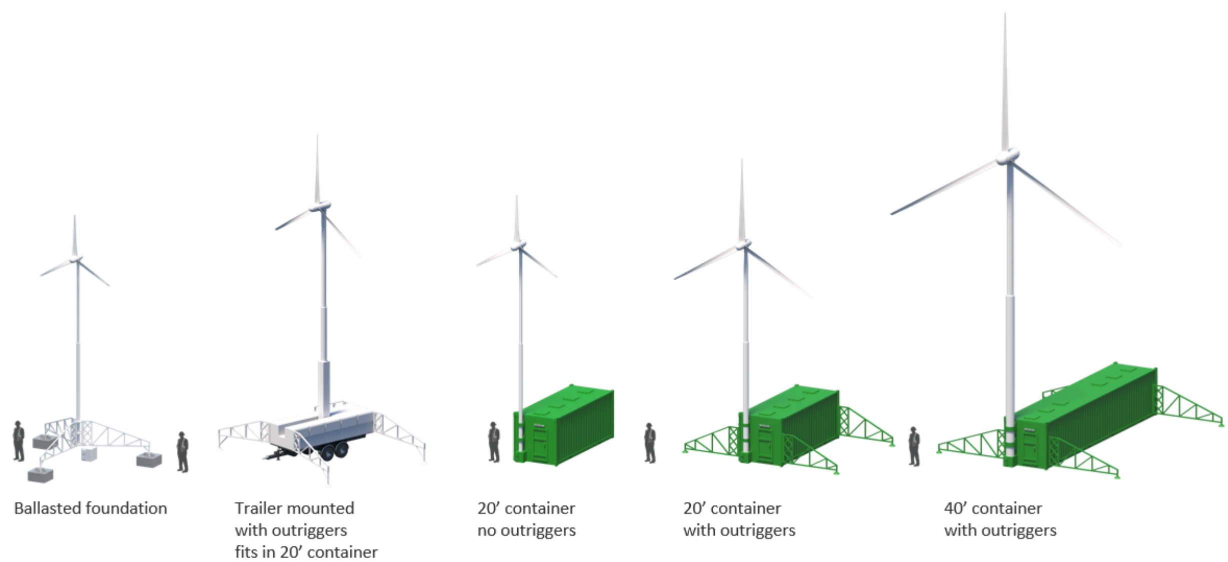

Figure 16. Summary of foundation options explored.

Overturning Summary

The graph in Figure 17 summarizes the results of the foundation modeling and analysis. As rotor diameter increases, the overturning moment increases. To maintain the minimum 1.5 factor of safety for the resistance to overturning as rotor diameter increases, outriggers are added, followed by earth anchors. The data from the foundation analysis can be found in Table 6.

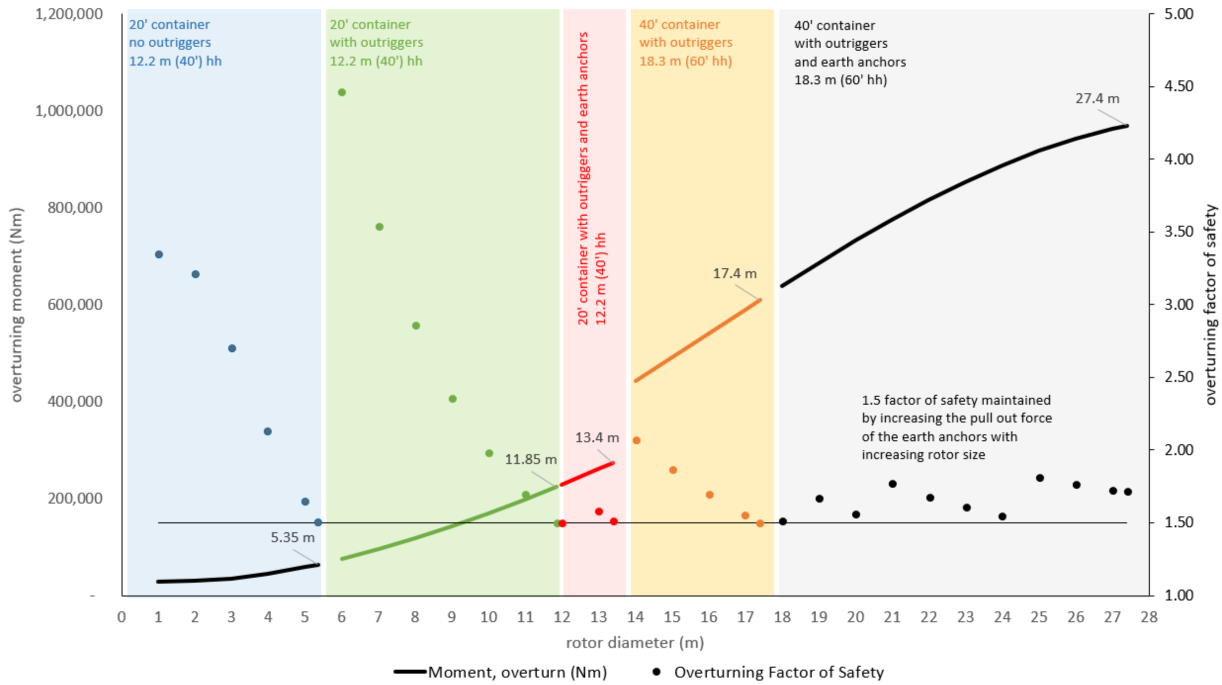

Figure 17. Overturning summary graph

Sliding Summary

The graph in Figure 18 summarizes the results of the sliding analysis. Assuming a coefficient of static friction of 0.5 and safety factor of 1, thrust forces in 44.7-m/s (100-mph) winds will not slide the 20-ft

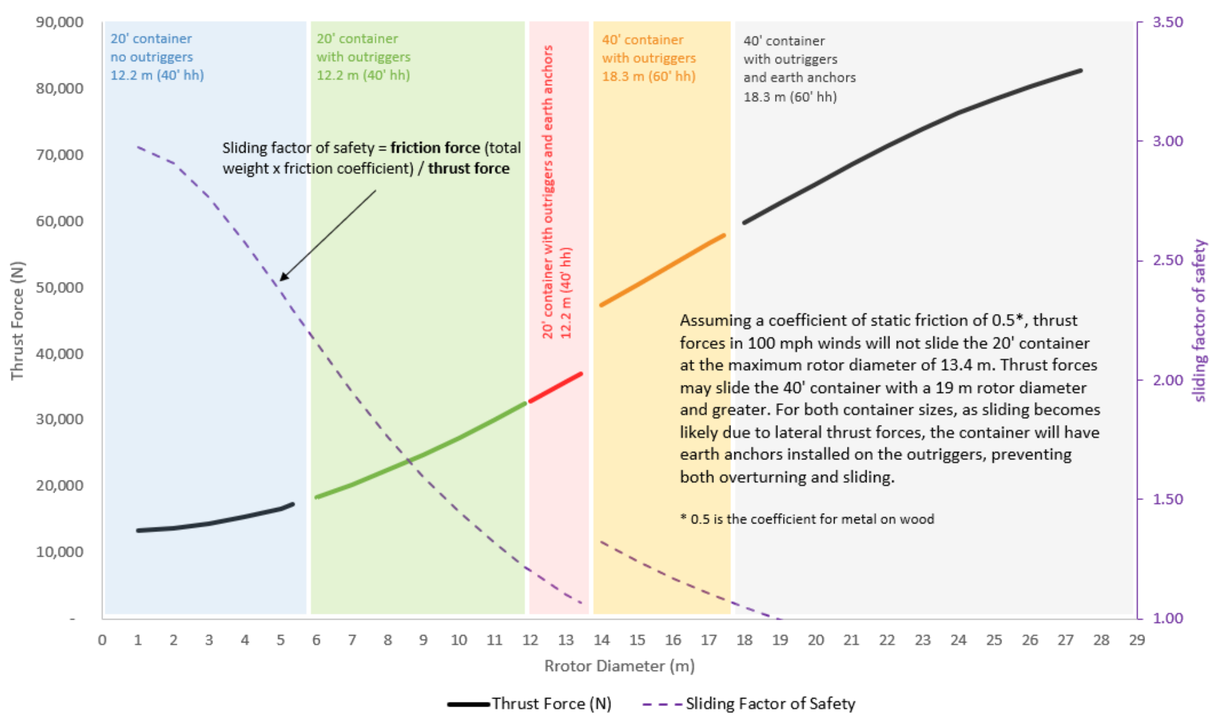

Figure 18. Sliding summary graph

container at the maximum rotor diameter of 13.4 m. Thrust forces may slide the 40-ft container beyond a 19-m (62.3-ft) rotor diameter. As sliding becomes likely due to lateral thrust forces, the container can have earth anchors or similar installed on the outriggers, preventing both overturning and sliding.

Table 6. Data Table for foundation analysis

Rotor diameter (m)	Moment, overturn (Nm)	Moment, resist (Nm)	Overturning Factor of Safety	Turbine Foundation	Hub Ht (m)	Pullout Capacity per Earth Anchor (N)	Pullout Capacity per Earth Anchor (lbf)	Thrust Force (N)	Friction Force (N)*	Sliding Factor of Safety
1	28,757	96,205	3.35	20' cont, no OR	12.2	-	-	13,253	39,454	2.98
2	30,042	96,205	3.20	20' cont, no OR	12.2	-	-	13,577	39,454	2.91
3	35,676	96,205	2.70	20' cont, no OR	12.2	-	-	14,272	39,454	2.76
4	45,339	96,205	2.12	20' cont, no OR	12.2	-	-	15,311	39,454	2.58
5	58,708	96,205	1.64	20' cont, no OR	12.2	-	-	16,668	39,454	2.37
5.35	64,204	96,205	1.50	20' cont, no OR	12.2	-	-	17,213	39,454	2.29
6	75,464	336,716	4.46	20' cont, with OR	12.2	-	-	18,316	39,454	2.15
7	95,283	336,716	3.53	20' cont, with OR	12.2	-	-	20,230	39,454	1.95
8	117,845	336,716	2.86	20' cont, with OR	12.2	-	-	22,382	39,454	1.76
9	142,828	336,716	2.36	20' cont, with OR	12.2	-	-	24,747	39,454	1.59
10	169,911	336,716	1.98	20' cont, with OR	12.2	-	-	27,298	39,454	1.45
11	198,772	336,716	1.69	20' cont, with OR	12.2	-	-	30,009	39,454	1.31
11.85	224,463	336,716	1.50	20' cont, with OR	12.2	-	-	32,419	39,454	1.22
12	229,091	343,169	1.50	20' cont, with OR and EE	12.2	756	170	32,854	*39,454*	1.20
13	260,545	412,642	1.58	20' cont, with OR and EE	12.2	8,896	2,000	35,805	*39,454*	1.10
13.4	273,372	412,642	1.51	20' cont, with OR and EE	12.2	8,896	2,000	37,010	*39,454*	1.07
14	442,368	914,405	2.07	40' cont, with OR	18.3	-	-	47,228	62,500	1.32
15	491,509	914,405	1.86	40' cont, with OR	18.3	-	-	50,315	62,500	1.24
16	540,907	914,405	1.69	40' cont, with OR	18.3	-	-	53,430	62,500	1.17
17	590,080	914,405	1.55	40' cont, with OR	18.3	-	-	56,547	62,500	1.11
17.4	609,579	914,405	1.50	40' cont, with OR	18.3	-	-	57,788	62,500	1.08
18	638,546	963,215	1.51	40' cont, with OR and EE	18.3	3,336	750	59,639	*62,500*	1.05
19	685,822	1,142,183	1.67	40' cont, with OR and EE	18.3	15,569	3,500	62,680	*62,500*	1.00
20	731,427	1,142,183	1.56	40' cont, with OR and EE	18.3	15,569	3,500	65,643	*62,500*	0.95
21	774,878	1,369,960	1.77	40' cont, with OR and EE	18.3	31,138	7,000	68,503	*62,500*	0.91
22	815,693	1,369,960	1.68	40' cont, with OR and EE	18.3	31,138	7,000	71,233	*62,500*	0.88
23	853,391	1,369,960	1.61	40' cont, with OR and EE	18.3	31,138	7,000	73,807	*62,500*	0.85
24	887,488	1,369,960	1.54	40' cont, with OR and EE	18.3	31,138	7,000	76,198	*62,500*	0.82
25	917,503	1,662,817	1.81	40' cont, with OR and EE	18.3	51,155	11,500	78,380	*62,500*	0.80
26	942,953	1,662,817	1.76	40' cont, with OR and EE	18.3	51,155	11,500	80,327	*62,500*	0.78
27	963,357	1,662,817	1.73	40' cont, with OR and EE	18.3	51,155	11,500	82,012	*62,500*	0.76
27.4	969,998	1,662,817	1.71	40' cont, with OR and EE	18.3	51,155	11,500	82,607	*62,500*	0.76
									**friction force is not accurate when earth anchors are present; sliding is assumed to be prevented by earth anchors*	

Airborne Wind Energy

The D3T team has explored airborne wind energy (AWE) as a potential option for deployable systems. These systems can be packaged and transported in shipping containers, and the container is often used as part of the foundation as depicted in Figure 19. Larger airborne systems can add outrigger structures to prevent overturning during high tether forces. Other systems transport and deploy from a trailer. These foundation structures are designed and engineered for the specific airborne systems and were not analyzed in this study.

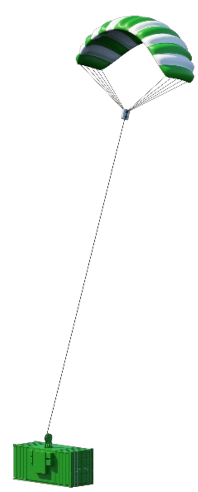

Figure 19. AWE

Other Considerations

When using a container or trailer as the foundation for a deployable wind turbine, the total system weight plays a large role in determining the resistance to overturing. Increasing the weight via ballasting or housing balance-of-system components in the container, such as batteries and inverters, will help increase overturning resistance. Outriggers and earth anchors can help stabilize the foundation, but another low-cost possibility could include utilizing additional containers as outriggers. Guy wires can also be added to enable a slenderer tower. Modeling assumed a three-bladed horizontal axis wind turbine; ducted turbines or high-solidity rotors will have increased thrust loading that should be considered in the foundation design. Although it may be possible to lower a deployable turbine system when extreme winds are anticipated, one does not always receive this warning, and designing reliance on reaction to such events could lead to unsafe operating conditions (scrambling to lower during a storm or overturning due to insufficient foundation design).

APPENDIX C. WIND RESOURCE ASSESSMENT AND SITING

The following resources offer data and guidance to support the wind resource assessment and wind system energy production estimation process as part of the mission planning stage of a potential wind turbine system deployment. Although it continues to improve with time, the quality of wind resource data can vary greatly across and within various databases, and high-quality data are often unavailable for remote locations. The best data are from actual site measurements collected at the height of the planned wind turbine over the course of at least a year, and generally multiple years, to capture not only the daily and seasonal variability, but also interannual variability of a site. This level of certainty is necessary for financing large utility wind farms, but if more uncertainty can be tolerated, there are much simpler estimates that can be used as described below.

C.1. Global Wind Atlas

The Global Wind Atlas [10] is a freely available, web-based wind resource and wind turbine energy production estimation tool. The Global Wind Atlas provides planners with the following information and capabilities in an online and downloadable format:

- Global onshore coverage and offshore coverage up to 200 km from the shoreline
- Wind resource mapping at 250-m horizontal grid spacing and at heights of 10, 50, 100, 150 and 200 m above ground/sea level
- Users can assess the wind resource at a point, over a custom area, or within a country or first administrative unit (e.g., state, province)
- Users can assess the variability of wind resource by year, month, and hour
- A custom wind turbine power curve can be input to provide an estimate of the energy production for any defined point or area
- Data can be downloaded in a geographic information system (GIS) format for use in other analysis platforms

The latest version of the Global Wind Atlas is available at: https://globalwindatlas.info/.

C.2. Wind Turbine Siting

After the decision to deploy a wind system has been made, there are additional considerations when selecting the exact location of a wind turbine installation at a base camp. Physical characteristics of the local area and base camp can impact the wind flow, and therefore the performance of a wind turbine. Vegetation and structures can obstruct the wind flow, and topographic features like hills or valleys can accelerate and direct the wind in a certain direction. Longer-term data collection methods commonly used in commercial development are unlikely to be feasible in the military planning process, but the use of some simpler qualitative guidance for on-site assessments can be beneficial. One such resource is *A Siting Handbook for Small Wind Energy Conversion Systems* [11], which is freely available online from the U.S. Department of Energy Office of Scientific and Technical Information (OSTI). The document can be found by searching by title or directly through this link: https://www.osti.gov/servlets/purl/5490541.

Another good general reference for the process of wind turbine site assessments is the *Small Wind Site Assessment Guidelines* [12], published by the National Renewable Energy Laboratory. The document is targeted at commercial small wind deployments, but much of the guidance is applicable to military mission planning as well. Being a newer document than the above reference, it also contains more updated references to commercial data providers and some recent case studies. The document is also available through the Office of Scientific and Technical Information site or directly at this link: https://www.osti.gov/biblio/1225476-small-wind-site-assessment-guidelines.

For longer-duration missions of a year or more, or, if the equipment or capabilities are available, there are additional methods to assess the local wind resource with higher accuracy to optimally place a wind turbine for maximum production. Wind speed measurements can be collected with temporary meteorological towers, lidar units using remote sensing methods to measure wind velocity from the ground, and possibly even drones with specialized sensors and software to process wind speeds during flight. Software tools are also available or in development that provide assessments of the impacts of local topology and obstructions, but require specialized skills and training to use effectively.

C.3. Estimated Wind Energy Calculation

The energy output of a wind turbine can be estimated using statistical techniques [13] that incorporate the wind turbine power curve and the wind resource probability distribution function, *p(V)*, through the function:

$$\overline{P}_w = \int_0^\infty P_w(V) * p(V)dV$$

Where:

$\overline{P}_w$ = average wind turbine power
P_w = wind turbine power output
V = wind speed
p = wind resource probability distribution function

The wind turbine power curve is typically derived empirically as part of a standardized field test to certify the turbine performance, but the theoretical turbine power production can be estimated by:

$$P_w = \frac{1}{2} * \rho * A * C_p * V^3$$

Where:

P_w = Wind turbine power output
ρ = air density
A = rotor swept area
C_p= coefficient of performance
V = wind speed

This function is valid from the cut-in (minimum) wind speed until the rated power of the wind turbine has been achieved, at which point the wind turbine remains at a constant rated power until the cut-out (maximum) wind speed.

The wind resource probability distribution can be measured directly from instruments in the field over the course of a year or more, but as a simple estimate, if the mean wind speed is known, a Rayleigh probability distribution function can be used as follows:

$$p(V) = \frac{\pi V}{2{V_m}^2} e^{-\pi V^2/(4{V_m}^2)}$$

Where:
p(v) = probability as a function of wind speed
V = wind speed
V_m = mean wind speed

This estimation method can be applied to a full year of operation to calculate the annual energy production of the wind turbine, but it does not account for various losses in a real operating system such as mechanical and electrical losses and also operational downtime. It is an upper bound estimate of the potential wind energy generation.

APPENDIX D. IEC WIND TURBINE STANDARDS

This appendix provides the key conclusions and recommendations for adapting the small wind turbine design standards to deployable turbine applications, particularly IEC 61400-2 Edition 3. Stakeholders vetting the recommendations could form the starting point for characterizing an S-class deployable small wind turbine. The key conclusion is that the framework provided by the existing IEC Standard has sufficient flexibility to be used as is with only minor and very specific potential deviations. Deployable turbines have different design drivers than standard wind turbines. In many respects, such as the need to accommodate a wide variety of environmental conditions, these drivers create design challenges. On the other hand, these drivers also provide flexibility not available when designing standard wind turbines (such as allowing for a shorter design lifetime or more frequent inspection intervals). The key challenge for designing a turbine for deployable applications is to articulate these design drivers and more carefully characterize the environment under which deployable turbines will be expected to operate.

D.1. Recommended Deviations From the IEC Standard

Extreme Wind Speed (As a Design Input) (See Clause 6.3.3.2)
As an input to the design loads, the IEC Standard (see clause 6.3.3.2) mandates the use of the 50-year wind speed (i.e., a recurrence interval of 50 years). This 50-year wind speed, referred to as V_{e50}, is calculated based upon the design reference speed, V_{ref}. Because deployable turbines can have shorter operational timespans, will generally run attended, and are likely to be easily tilted down or dismantled, use of a lower extreme wind speed, and thus a shorter recurrence interval, is appropriate. The D3T team recommends use of a recurrence interval of 1–5 years. It should be noted that the IEC Standard provides formulas to calculate V_{e50} and V_{e1} but does not provide a formula for calculating V_e for an arbitrary recurrence interval. The value of V_e will be used in clauses 7.4 and 7.5 to calculate extreme loads. If the calculated extreme loads lead to significant design requirements for the deployable turbine, it could be worthwhile to calculate an appropriately shorter recurrence interval in line with the design life of the turbine to reduce the required structural weight, for example.

D.2. Recommendations for Working Within the IEC Standard

SWT Class (Clause 6.2)
For design purposes, the IEC Standard provides four standard wind classes, labeled (from most to least windy) I, II, III, and IV. In addition, the IEC Standard provides the option to define a nonstandard, S-class, small wind turbine. Due to their unique requirements, it is recommended that deployable turbines be designed as S-class.

Turbulence Intensity (Clause 6.2, Annex L)
Another design parameter is the turbulence intensity when the wind speed is 15 m/s, referred to as I_{15}. The minimum value for I_{15} is 0.18. However, because deployable turbines may be installed in complex terrain or within some level of ground clutter (such as trees and/or buildings), and are likely to be mounted on shorter towers, a higher value of I_{15}, say 0.25–0.3, is recommended.

Other Normal Environmental Conditions (Clause 6.4, Annex J)
Values for the IEC Standard Normal Environmental Conditions are summarized in Table 7. DoD climate categories are defined in MIL-STD 810H. Comparison of the two documents shows that the IEC Standard "extreme temperature" range is comparable to the combined "Basic" plus "Hot" climate conditions ambient temperature range as defined in MIL-STD 810H.

Table 7. Normal Environmental Conditions

Temperature: Normal environmental conditions temperature range: −10°C to +40°C NOTE: The "normal conditions temperature range" and the "extreme temperature range" do not necessarily specify the operating range of the turbine. Rather, these ranges are used in calculating loads. A turbine should be able to withstand exposure to the extreme temperature range without damage (even if not operating when it is too hot or too cold). This does raise the question of specifying a temperature range over which a turbine can operate. Consider adoption of the "extreme temperature range" as the operating temperature range. This may require placing the controls and power electronics in a conditioned container or reducing the maximum operating range temperature from 50°C to 40°C.
Humidity: Up to 95%. NOTE: Probably OK.
Atmospheric Content Equivalent to that of a nonpolluted inland atmosphere (See IEC 60721-2-1). NOTE: May need a tighter specification for operation in more polluted environments. Many operations occur in polluted environments.
Solar Radiation Solar radiation intensity of 1,000 W/m^2. NOTE: May need to specify a higher value to account for desert environments.
Air Density Air density of 1.225 kg/m^3. NOTE: This is the air density at sea level. This spec is probably OK as long as the turbine also has adequate performance at higher elevations where the air density is lower.

Other Extreme Environmental Conditions (Clause 6.4, Annex J)

This clause lists various extreme environmental conditions for which a turbine may need to be designed. These are listed in Table 8. For most of the items, the IEC Standard provides only a qualitative discussion. If a given item is of importance to a deployable turbine, further research and analysis will be required to develop a quantitative specification.

Table 8. Extreme Environmental Conditions

Temperature IEC "Extreme Temperature Range" defined as "at least −20°C to +50°C." NOTE: Recommend keeping this range for the loads calculations; consider adopting this range as the operating range.
Lightning Requirements of clause 9.5 usually adequate. NOTE: Probably OK.
Icing No icing requirement for SWT classes. If this is a concern, recommend estimating a minimum of 30-mm layer of ice with a density of 900 kg/m^3 on all exposed areas (including tower and guy wires). This static ice load would be combined with drag loads on the parked turbine system at $3 \times V_{avg}$.
Earthquakes SWT classes have no minimum standard. Probably not necessary to consider, other than placement sufficiently far from personnel housing.

Miscellaneous Environmental Conditions (Clause 6.4 plus various other clauses)
In addition to the aforementioned items, the IEC Standard refers to other possible environmental conditions. These miscellaneous conditions are listed in Table 9.

Table 9. Miscellaneous Environmental Conditions

Rain, hail, snow, and ice NOTE: A deployable turbine will need to be able to operate with some level of precipitation (in all its forms).
Mechanically active particles (sand, dust) NOTE: It is highly likely that a deployable turbine could be installed in a sandy or dusty environment.
Marine environment – corrosion NOTE: Because it is possible that a deployable turbine could be installed in a corrosive environment, a stringent corrosion specification is recommended.
Soil conductivity (Clause 9.4) NOTE: Need to adequately ground the turbine, even with poor soil conditions.

Electrical Load Conditions (Clause 6.6)
For battery charging applications, it is recommend to use the "Battery Charging" conditions (clause 6.6.31) either as is or as a starting point. For all other turbines, it is recommended to use either the "Extreme Electrical Conditions" (clause 6.6.2.2) or "Local Grid" (clause 6.6.3.2) on a continuous basis and comply with the UL1741 SB grid support requirements as a minimum.

Support Structure (Clause 10)
For rotors with a swept area greater than 2.0 m^2, the tower must be analyzed along with the turbine as a system. Although it may not prove significant, including the tower as part of the system for all turbine sizes is recommended, including smaller turbines below the 2.0-m^2 rotor swept area threshold.

Characterization of an S-Class Deployable Turbine
As stated earlier, although the IEC Standard defines four standard classes of turbines, I–IV, it also allows for the characterization of S-class turbines. The items discussed here can form a starting point for characterizing an S-class turbine for deployable applications. Annex B in the IEC Standard provides a list of the design parameters needed to characterize an S-class turbine.

APPENDIX E. POWER SYSTEM INTEGRATION STANDARDS

The following list of standards includes those mentioned in the design guidelines text, sometimes with more details and also some additional relevant standards not mentioned in the main text.

Tactical Microgrid Standard (draft)
The (draft) Tactical Microgrid Standard (TMS) establishes the communication and control interface requirements for tactical microgrid components to operate as a single entity producing electricity in a tactical environment.

From the foreword to the draft standard:

> *The standard is [not yet] approved for use by all Departments and Agencies of the Department of Defense (DoD). The standard establishes criteria to enable the interoperability of hardware and software necessary to operate a tactical microgrid on the battlefield with respect to the design, intelligent control, stability and performance, security, safety of personnel, and the protection of the tactical microgrid systems and equipment. The standard defines the tactical microgrid architecture using open standards to support a modular, highly cohesive system structure in order to leverage the collaborative innovation of industry, academia, and government participants along with stakeholders. The document is intended to be free of Essential Patent Claims. Although development of this standard was made with the active participation of the Private Sector, non-government contributors have certified that they have declared all essential patent claims found in this standard.*

It was important that the TMS be free of Essential Patent Claims because past power systems such as the AMMPS generators have proprietary communication and control protocols that limit the development and application of microgrids by other vendors and DoD.

TMS lists wind turbines as Type I – Power Generation Sources, which according to TMS 4.2.1 means:

> *Type I Power Generation Source has the capability to operate as an individual power source or can be synchronized to provide power as a TMG. As an individual power source, they can be used to provide power to a single load such as a shelter or radar system. As an element of the TMG, multiple power sources can be synchronized and controlled to turn on and off based on the load on the TMG.*

Although this definition may be good for the purposes of TMS, many standard wind turbines are not able to operate independent of a wider grid and cannot support a single load without additional hardware, energy storage, and/or a dispatchable energy source. The TMS should be further developed to account for these features of wind turbines. Similar issues are also present with solar energy sources.

TMS Appendix A. General Data Model Requirements
The TMS states:

> *The TMS defines an architecture for building microgrid systems. Each microgrid system defines one or more devices that connect together. Each device implements a single role that provides a modular unit of functionality. Each role has defined interfaces that support both standalone and coordinated behaviors. Multiple devices, implementing the same or different roles, may be packaged together into a single platform. This architecture is designed to enable interoperability between devices and platforms from all systems, subject to power constraints.*
>
> *Individual devices perform essential TMS functions using only internal inputs and outputs. System-level TMS performance may be enhanced by sending coordination messages between devices. The TMS data model defines the*

language for these messages. The data model is defined in terms of data flows and data types. Data flows define the motion of messages while data types define the contents of messages.

Much of the TMS defines the TMS Data Model. In TMS A.1, the TMS:

> *defines the data model, including all messages sent between TMS devices. These messages are used to communicate all system health, status, command, and control information. They are also recommended for communications with external networks. The data model provides a common language used by all TMS devices. It is platform-independent to allow flexibility in device design and implementation. It contains detailed data flow and data type definitions to guarantee interoperability between devices, regardless of make or model.*
>
> . . .

There are two types of device roles in TMS: Control Services and Power Devices. Figure 20 shows the relationship between these roles.

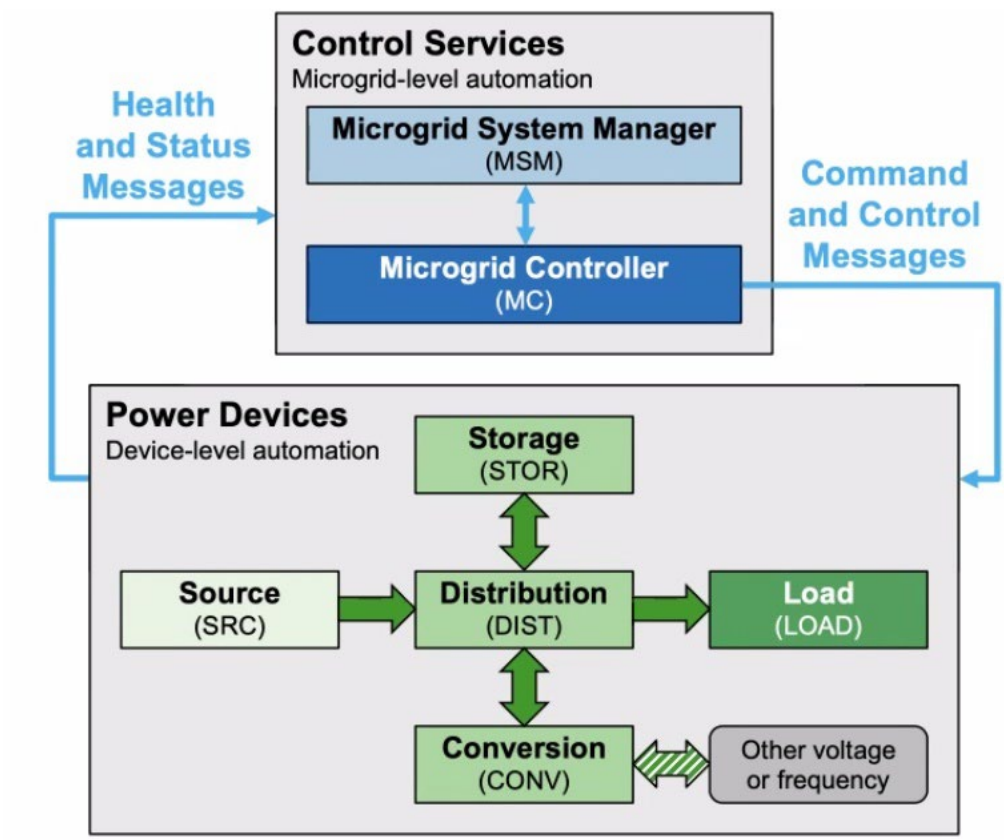

Figure 20. TMS Device Roles (TMS Appendix A.6)

Under TMS A.6.2,

> *Source (SRC) devices provide power to the microgrid and include diesel gensets, solar panels, and* ***wind turbines****. Note that while an energy storage unit (ESU) can act as a source, TMS considers ESUs exclusively as Storage device roles."*

TMS Appendix B. Detailed Data Model Requirements

Figure 21 shows the major hardware components in the source (SRC) device role.

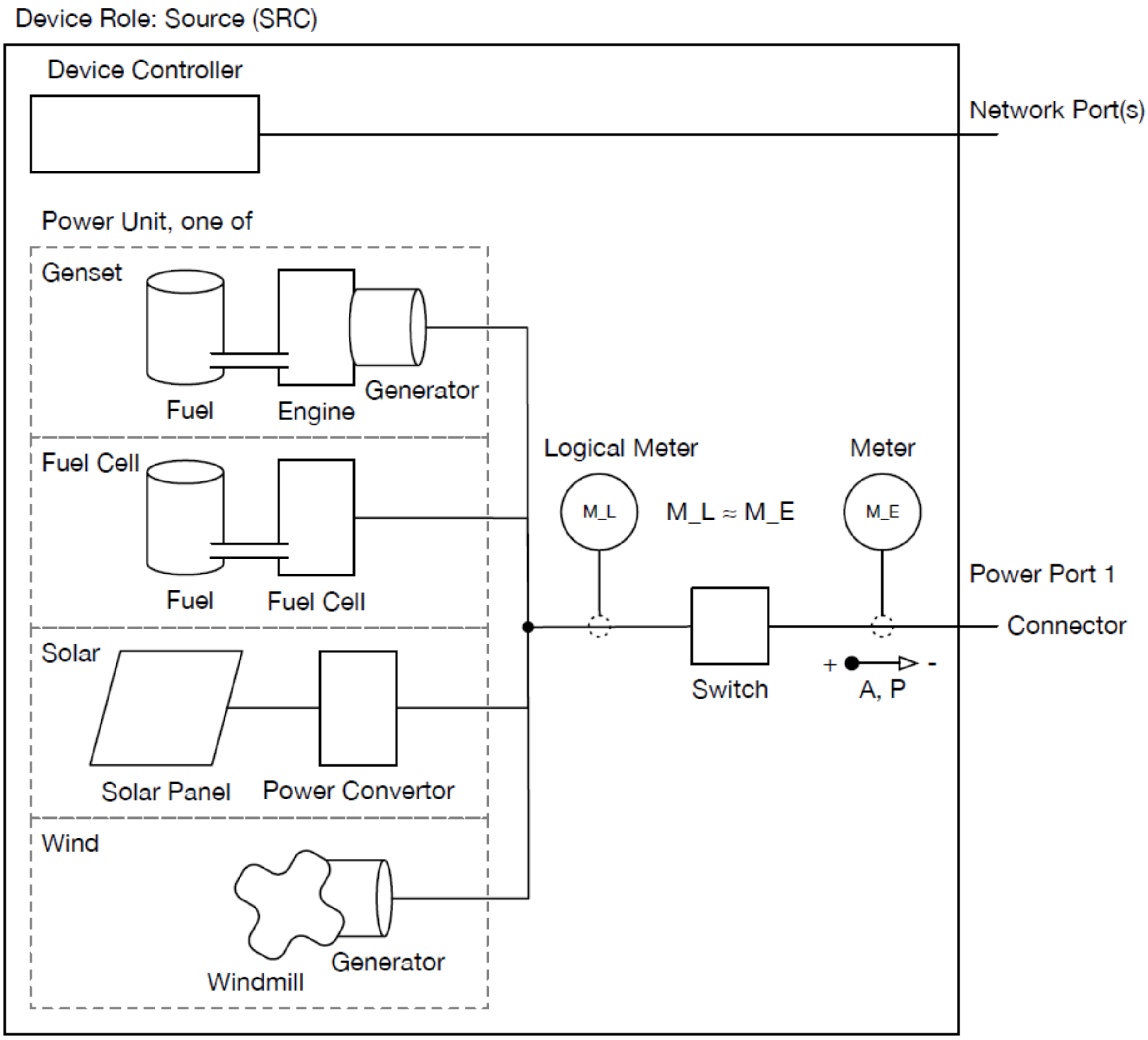

Figure 21. Schematic diagram of the source device role (TMS B.1.1)

From TMS B.1.1,

> *Every source device shall have a Device Controller that connects to the TMS network. This is the entry point to the data model. The Device Controller's function is to send and receive messages, translating as necessary between external messages and internal signals.*

Thus, a wind turbine operating on a tactical microgrid will need to implement a device controller, logical meter, switch, meter and power port that are TMS-compliant. Schweitzer Engineering Laboratories has produced PowerMAX, a microgrid control and smart relay system, implementing TMS for several devices/generators. Thus, wind turbine producers might be able to source the required TMS-compliant interface and control components instead of developing these devices themselves. Because the TMS is an open standard, other vendors can also create and offer product solutions, thereby creating competition and eliminating sole-sourcing concerns.

Also, from TMS B.1.1,

> *Every source device shall have at least one network port. More network ports may be required to allow for connections to multiple TMS devices. Every source device shall have some form of power unit, usually a generator set (genset), fuel cell, solar, or wind power source. At present, the data model provides the most detailed support for gensets.* ***More support for other power units may be added in future versions of this standard.*** *The TMS data model provides support for monitoring the energy source (fuel level) and also for starting, stopping, and regulating the amount of power produced* [emphasis added].

There are some differences between diesel generators and wind turbines that should be addressed within the TMS. For instance, the microgrid controller expects to be able to send a load-sharing request to a power source and the source is expected to reply. This is logical for a diesel generator; however, unless a wind turbine has combined energy storage or active controls to curtail power production, the wind turbine cannot respond to load-sharing requests. Similarly, some wind turbines should not be disconnected from the grid frequently. Although the TMS allows for "Start" and "Shutdown" functions for Type I power sources, these alone are not sufficient for a non-dispatchable power source such as a wind turbine. The microgrid controller should be implemented in such a way that the power switches connecting the wind turbine to the microgrid do not unnecessarily disconnect the wind turbine and cause damage.

Section 5.2.66 defines power source features where it is possible to specify whether the source is a genset, fuel cell, solar source, wind source, or source shared with a vehicle powertrain.

Section B.5.2.12 defines power hardware information under B.5.2.1 device information and includes information such as fuel and engine information. This section could be expanded to have information relevant to wind turbines.

National Electrical Code (NEC): Installation and Equipment Standards

The NEC is a standard for the safe installation of electrical wiring and equipment in the United States adopted by local states and municipalities and frequently referenced in DoD specifications. The local authority having jurisdiction (AHJ) inspects for compliance with these standards. Wind systems are installed to meet the NEC, the latest being NFPA 70: NEC 2020. The most relevant sections for wind energy are:

- 694 Wind Electric Systems
- 705 Interconnected Electric Power Production
- 706 Energy Storage Systems
- 710 Stand Alone Systems
- 712 Direct Current Microgrids

To pass inspection, the wind turbine electrical equipment, most notably the inverter, must have been tested to meet:

- IEEE 1547-2018 - IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces

- UL 1741: Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources
- The communications requirements in IEEE 2030.5-2018 - IEEE Standard for Smart Energy Profile Application Protocol

IEEE 1547-2018 Standard for Interconnecting Distributed Resources with Electric Power Systems

The IEEE 1547-2018 standard provides a uniform standard for interconnection of distributed resources with electric power systems. It provides requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection [6]. This standard is being adopted widely in commercial applications, and the same functionality may be leveraged in a military context in the absence of a specific military specification such as the Tactical Microgrid Standard.

IEEE 2030 Standard for the Specification of Microgrid Controllers

A key element of microgrid operation is the microgrid energy management system (MEMS). It includes the control functions that define the microgrid as a system that can manage itself, operate autonomously or grid-connected, and seamlessly connect to and disconnect from the main distribution grid for the exchange of power and the supply of ancillary services. The scope of the IEEE 2030 standard is to address the functions above the component control level associated with the proper operation of the MEMS that are common to all microgrids, regardless of topology, configuration, or jurisdiction [7].

MIL-STD-705D, Department of Defense Test Method Standard: Mobile Electric Power Systems

This standard covers eight series of specific methods for testing and determining the characteristics of Mobile Electric Power Systems (MEPS). This standard establishes test methods for determining characteristics desired by the military departments to ensure that the MEPS complies with military requirements. This standard establishes uniform methods for the military services, uniform test equipment and facilities, and uniform procedures for setting up and conducting the various tests. These methods provide for conservation of human-power, materials, equipment, and facilities. This standard does not establish limiting values for the results of the tests, nor does it specify the test required for any specific MEPS.

APPENDIX F. MILITARY REFERENCE DOCUMENTS

Access to military standards and specifications is available online through the ASSIST web portal (https://quicksearch.dla.mil/qsSearch.aspx). ASSIST is a website used by standardization management activities to develop, coordinate, distribute, and manage defense and federal specifications and standards, military handbooks, commercial item descriptions, data item descriptions, and related technical documents prepared in accordance with the policies and procedures of the Defense Standardization Program (DSP). Besides DoD-prepared documents, ASSIST also has selected international standardization agreements, such as North Atlantic Treaty Organization (NATO) standards ratified by the United States and International Test Operating Procedures.

The following list of standards includes those mentioned in the design guidelines text, sometimes with more details and also some additional relevant standards not mentioned in the main text.

F.1. Logistics and Transportation

Army Container Operations ATP 4-12 (May 2013)
Army Techniques Publication (ATP) 4-12, Container Operations [3], is the Army's doctrine for container management during operations, and ensures that unit equipment and supplies are delivered in a timely and secure manner to the intended destination. To minimize intermodal logistics constraints, the Army uses standard 20-foot International Organization for Standardization (ISO) steel containers to move materiel. Although larger 40-foot ISO containers have been used in the past, DoD has removed them from their inventory to simplify handling equipment. Commercial 40-foot containers may be used to ship items to a primary logistics port, but the container handling equipment at more forward operating locations is limited to the 20-foot containers.

Army Cargo Specialists' Handbook FM 55-17 (1999)
This Army field manual covers cargo handling specifications for intermodal transportation of material. Part 4 of the manual discusses air transport on common cargo handlers like the C-130 aircraft. These platforms use a standardized pallet system named the 463L. The 463L pallet dimensions are 108 inches by 88 inches by 2 1/4 inches. It weighs 337 pounds and has a total load capacity of 10,000 pounds, with a desired load capacity of 7,500 pounds.

Air Force Interservice Manual 24-204: Preparing Hazardous Materials for Military Air Shipments (July 2018)
Additional details on the shipment of lithium batteries and magnetic materials can be found in the following sections:

- ***Section 3.5.1.6:*** *Lithium batteries installed in electronic equipment battery box or compartment require no additional packaging. Individuals may hand carry (pockets, rucksack, backpacks, etc.) the minimum number of spare lithium batteries required to sustain the immediate operation (as determined by the troop commander). Pack hand-carried lithium batteries in original wrapping or in nonconductive material to prevent external short-circuiting. Prepare equipment containing lithium batteries, not considered individual issue or basic combat, according to A13.7, A13.8, or A13.9.*
- ***Section A3.3.9.2:*** *Lithium Batteries. Lithium cells or batteries must be of a design type proven to meet the requirements of the UN Manual of Tests and Criteria that were in effect based on the date of manufacture. Manufacturers must maintain a record of satisfactory completion of these tests prior to offering the cell or battery for transport. Manufacturers retain this record for as long as that lithium battery design type is offered for transportation and for 1 year thereafter.*

- ***Section A3.3.9.2.1:*** *Requirements for Lithium Batteries. Lithium batteries must:*
  - *Incorporate a safety venting device or otherwise be designed in a manner that will preclude a violent rupture under conditions normally incident to transportation.*
  - *Be equipped with an effective means of preventing external short circuits.*
  - *Be equipped with an effective means to prevent dangerous reverse current flow (e.g., diodes, fuses) if a battery contains cells or a series of cells that are connected in parallel.*
  - *Lithium batteries identified as defective for safety reasons (e.g., manufacturer recall) or that have been damaged, or that have the potential of producing a dangerous evolution of heat, fire, or short circuit are prohibited from air movement.*

  This list is not all-inclusive, and many more details are in TM 38-250. Some of the details not included are requirements for drop tests, maximum number of cells per package, weight limits, and others. Many of these requirements may not apply as there is an equipment exemption.
- ***Section A3.3.9.3:*** *Magnetized Material. Any package that has a magnetic field strength of more than 0.00525 gauss measured at 4.5 m (15 ft) from any surface of the package is forbidden on military aircraft. If a wind turbine utilizes permanent magnets in stator/rotor and the magnetic field is strong enough, it may not be permitted to be transported by military aircraft. Investigation into how these limits on magnetic field strength may inhibit the transport of wind turbines was done.*

Code of Federal Regulations (CFR) 172.101 & 173.185: Hazardous Materials & Lithium Cells and Batteries

When transporting lithium-ion batteries or other hazardous materials in the public space, they must be done so in accordance with these regulations. Much of these regulations may affect the lithium battery cell manufacture more than the integrator, but the regulations must be acknowledged. From an integrator standpoint, lithium cells or batteries contained in equipment must be packaged in a manner to prevent:

- Short circuits
- Damage caused by movement
- Accidental activation of the equipment

For lithium batteries used in equipment, they must be placed in non-metallic inter packaging that completely enclose the cells or batteries and prevent contact with equipment or other electrically conductive materials. Other limits such as size and weight limits are included in this code of regulations.

General Transportation Guidance for Deployable Wind Systems

- Transportability: The D3T system specializes in being deployable, and depending on the configuration, it will be held to different standards. The most basic standard is MIL-STD-1366E, "Interface Standard Transportability Criteria," guidance on transportability. This standard contains the requirements for all modes of transportation in the Defense Transportation System (DTS). This includes transportation testing, over-the-road requirements, rotary and fixed-wing aircraft requirements, as well as tiedown and lifting requirements.
- Transport Configuration: While in transport, all hatches, dust covers, cable access, and screens should have a tightening mechanism to secure them. The unit should be powered down with the energy storage system isolated.
- Transport Turbulence: The D3T should be designed to meet MIL-STD-810H, Method 514.8, Annex C, Category 4 Vibration Testing without a loss of performance.

- Secured Cargo Transport: The D3T transport container should prevent the unit from shifting, rattling, or receiving damage while in transit.
- Forklift Transport: The military operates forklifts to maneuver 20-ft containers at most bases. The D3T container should have clearly identifiable forklift pockets.
- Highway Transport: The D3T is required to be transported with all military vehicles able to meet the 20-ft container requirements. Equipment examples include the M870 on-highway trailer and the Heavy Expanded Mobility Tactical Truck for rough terrain.
- Fixed Wing Air Transport: A 20-ft container can be transported by air using the C-130 and C-17 aircraft. Therefore, the D3T will be subject to MIL-STD-1791C Internal Aerial Delivery in Fixed Wing Aircraft.
- External Helicopter Transport: A 20-ft container can be transported by air using the CH-53 and MV-22 helicopters. Therefore, the D3T will be subject to MIL-STD-209K Lifting and Tie Down Provisions for helicopter sling loads.
- Rail Transport: MIL-STD 1366E provides guidance and regulation on shipping within the United States and to NATO countries by railway. A 20-ft container is standard equipment if the weight limit is not exceeded. Additionally, the dimensional requirements for railway cargo are available from the Association of American Railroads.
- Trailer Considerations: Trail-mounted units should have at pinnal hitch, standard trailer lights, and a max rated speed label.

F.2. Design and Manufacturing

MIL-STD-130: Identification Marking of U.S. Military Property
This standard provides the criteria by which product designers develop specific item identification marking requirements. Product designers must include in product definition data the specific requirements as to marking content, size, location, application process, and any required marking materials that will be part of the deliverable item. Simply stating in the product definition data that the marking be in accordance with this standard is not sufficient for initial design, development, and manufacture or subsequent production and procurement of replenishment spare items.

MIL-STD-171: Finishing of Metal and Wood Surfaces
The purpose of this standard is to establish finish system codes that link or cross-reference specific specification information for finishing and otherwise treating metal and wood surfaces. It also serves as a general guide to the selection of suitable finishing materials, procedures, and systems. It covers both organic (paint, varnish, and the like) and inorganic (metal plating, phosphatized metal, and the like) coatings.

MIL-STD-889: Dissimilar Metals
This standard defines and classifies dissimilar metals, and establishes requirements for protecting coupled dissimilar metals, with attention directed to the anodic member of the couple against corrosion.

MIL-STD-1472: Design Criteria Standard for Human Engineering
This standard establishes general human engineering design criteria for military systems, subsystems, equipment, and facilities. Definitions for a four-man lift and a light tactical trailer are included in this standard.

MIL-PRF-31032 Printed Circuit Board, General Specification
This specification establishes the general performance requirements for printed circuit boards or printed wiring boards and the verification requirements for ensuring that these items meet the applicable performance requirements.

MIL-DTL-38999M: Detail Specification for Electrical Connectors
This specification covers four series of miniature, high-density, circular, environment-resistant electrical connectors with removable crimp contacts, or hermetically sealed electrical connectors with fixed, nonremovable contacts. Both environment-resistant and hermetically sealed connectors are available with bayonet, threaded, or breech-coupled mating systems.

AMCP-706-360 Engineering Design Handbook; Military Vehicle Electric Systems
This document would be relevant if designing a system that integrates into a vehicle, as it describes characteristics of loads and transients.

F.3. Installation and Operations

ATP 3-37.10/MCRP 3-40D.13: Base Camps
This publication is a compilation of tactics, techniques, and procedures (TTP) found in doctrine, lessons learned, and other material that provides an integrated and systematic approach to base camps. Although all base camps may be unique, this document provides best practices to a commanding officer at the deployment of a base camp. Using this document may be useful to better tailor a deployable wind turbine design to fit within the design criteria of a military base camp.

MIL-STD-461: Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment
This standard covers the requirements and test limits for the measurement and determination of the electromagnetic interference characteristics (emission and susceptibility) of electronic, electrical, and electromechanical equipment.

MIL-STD-464: Electromagnetic Environmental Effects Requirements for Systems
This standard establishes electromagnetic environmental effects (E3) interface requirements and verification criteria for airborne, sea, space, and ground systems, including associated ordnance.

ATP 3-34.45 / MCRP 3-40D.17: Electric Power Generation and Distribution
This military publication codifies lessons learned and serves commanders and their staffs as a comprehensive guide for planning, producing, distributing, and managing electrical power in support of military operations, including contingency basing.

STP 9-91D13-SM-TG: Soldier's Manual and Trainer's Guide, Tactical Power Generation Specialist 91D
This publication is for soldiers holding Military Occupational Specialty (MOS) 91D and for trainers and first-line supervisors. It contains standardized training objectives, in the form of task summaries, to train and evaluate soldiers on critical tasks related to setting up, operating, and maintaining tactical power generation equipment, such as mobile diesel generators.

F.4. Electrical Components

One use case for smaller deployable wind systems is recharging batteries. Although there has been some effort to reduce the variety of battery formats across DoD, there remains a wide variety. What follows are some of the more common formats and devices.

BB-2590 Rechargeable Li-Ion Battery
The BB-2590 battery is a commonly used battery for various military applications. The most common use for the BB-2590 is radio communication systems.

STANAG-4015 Starter Battery
STANAG-4015 is a specification for NATO tactical vehicle batteries. Tactical vehicles are considered a potential element in a microgrid power system.

ELI-1614 & ELP-1614 Soldier Conformal Wearable Battery
With increased power requirements at the individual soldier level, DoD is interested in advancements in soldier wearable battery packs. The 1614 and other wearable battery packs are not yet widely deployed, but this is an active area of research and development.

AN/PRC-148 et al. Handheld Radio
The AN/PRC-148 is the most commonly fielded handheld radio by NATO forces. The handheld radio and others like it routinely need to be recharged in the field

MIL-PRF-32565: Performance Specification Battery, Rechargeable, Sealed, 6T Lithium-Ion
This performance specification contains general requirements for secondary (rechargeable) nominal 24-volt lithium-ion batteries having the 6T form factor in accordance with STANAG 4015. The batteries described in this specification are intended to be used as power sources for automotive starting, lighting, and ignition, as well as auxiliary electronics (such as deep cycle and silent watch operations with the vehicle engine off). This specification groups batteries into three types according to their minimum capacity and maximum Hazard Severity Level as defined by SAE J2464 for the overcharge abuse and battery nail penetration safety tests specified in this document: Type 1 has a minimum capacity of 55 Ah and maximum Hazard Severity Level of 4 for overcharge and battery nail penetration; Type 2 has a minimum capacity of 55 Ah and maximum Hazard Severity Level of 6 for overcharge and battery nail penetration; and Type 3 has a minimum capacity of 90 Ah and a maximum Hazard Severity Level of 6 for overcharge and battery nail penetration.

MIL-STD-1275E Department of Defense Interface Standard: Characteristics Of 28 Volt DC Electrical Systems in Military Vehicles
This standard covers the limits of transient voltage characteristics and steady-state limits of the 28-volt DC electric power circuits of military vehicles.

Photovoltaic Systems
Photovoltaic systems have been more widely used for military applications, and as a result of that experience, additional guidance has been developed to address performance gaps due to the unique military application. The U.S. Army develops Test Operations Procedures (TOPs) to detail specific performance testing for various systems to undergo prior to being deployed widely in military applications. A recent TOP has been released that addresses environmental testing for photovoltaic panels. Although a TOP does not yet exist for wind turbines, the photovoltaic TOP does provide some

valuable insight into the expected performance of a renewable system under various environmental conditions.

TOP 09-2-291 Environmental and Performance Testing of Photovoltaic Systems
This document describes procedures for conducting environmental and performance tests for fixed photovoltaic systems used in fixed and dismounted operations. These tests involve characterizing performance under various solar incidence conditions, as well as under unique environmental abuse conditions.

APPENDIX G. MILITARY HYBRID MOBILE POWER SYSTEM PROGRAMS

Solar Portable Alternative Communication Energy System (SPACES)
The United States Marine Corps (USMC) developed the Solar Portable Alternative Communications Energy System (SPACES) is a lightweight, portable, renewable energy system designed to provide power for platoon and squad-size units operating in remote locations. Marines use SPACES to recharge batteries for communications equipment like satellite communication radios, reducing the number of batteries carried on extended patrol. SPACES can manage up to 400 watts of power generated from lightweight, durable solar panels and provides a regulated 24-V DC output to energize battery-operated weapon systems. SPACES is fielded with an expanded assortment of components and enhanced charging profiles to increase the battery charging efficiencies. SPACES II can energize human-packed and handheld tactical radios and laptop computers, charge multiple battery types, and convert 24-V DC to 115-V AC for limited AC power requirements.

More information:
https://www.hqmc.marines.mil/e2o/Fleet/.

Deployable Renewable Alternative Energy Module (DREAM)
The Marine Corps Systems Command developed the Deployable Renewable Energy Alternative Module in 2008. The system was towable by vehicle and employed solar, wind turbine, battery, and generator technologies to temporarily power radios or computers until fuel can be resupplied to forward-deployed locations in Iraq. The system was designed to provide 3-kW continuous power to ensure greater than 15 days without the need for fuel resupply.

More information:
https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2007/power/NDIAGrandExhibitHall/Wed/Session16firstSolarPowerAdaptersandDREAMMorris.pdf.

Ground Renewable Expeditionary Energy Network System (GREENS)
The USMC developed the Ground Renewable Expeditionary Energy Network System (GREENS) as a portable power generation system that incorporates solar panels, energy storage, and AC/DC power sources. GREENS provides an average continuous output of 300 W—enough to power a battalion combat operations center (COC). Marines also use GREENS to power HIMARS and M777 howitzers, eliminating the need to tow a 3-kW generator and reducing vehicle idle time.

More information:
https://www.onr.navy.mil/en/About-ONR/History/tales-of-discovery/ground-renewable-expeditionary-energy-network-system.

Mobile Electric Hybrid Power Sources (MEHPS)
The USMC developed the Mobile Electric Hybrid Power Sources (MEHPS) power generation system combining batteries, solar, and smart controls with traditional diesel generators. The system has demonstrated up to 50% fuel savings and up to 80% reduced generator run time. The Marine Corps is working closely with the Army to develop field hybrid power systems and joint requirements for both that will increase the combat effectiveness of both services.

More information:
https://www.hqmc.marines.mil/Portals/160/FINAL%20MEHPS%20Brief%20to%20Industry_0201.pdf.

Renewable Sustainable Expeditionary Power (RSEP)
The Office of Naval Research managed this 5-year program to develop a 3–5-kW trailer-mounted solar-diesel hybrid system to support marines on a 15-day mission without needing fuel resupply. A prototype was tested at the Naval Surface Warfare Center, Carderock Division in 2017 and featured a solid-oxide fuel cell that could use diesel fuel and be paired with a solar electric system.

More information:
https://www.dvidshub.net/news/224539/demonstration-sofc-hybrid-power-system-held-carderock.

Transportable Hybrid Electric Power System (THEPS)
The Army's Rapid Equipping Force developed five Transportable Hybrid Electric Power System units, known as THEPS, in 2006. These systems provide about 250 kilowatts of continuous power from renewable sources such as wind, the sun, fuel cells, and large batteries and were designed to be deployed to Iraq to reduce the dependence and risk of fuel resupply missions.

More information:
https://www.afcea.org/content/conservation-innovation-fuel-defense-energy-efforts.

Energy to the Edge (E2E)
In 2012, the Army Rapid Equipping Force (REF) initiated the Energy to the Edge (E2E) program and contracted civilian personnel to act as Operational Energy Advisors to power very remote combat outposts throughout Afghanistan. The focus was on "the Edge"—those forward bases on the far reaches of operations. These locations are constrained due to difficult logistic resupply efforts that often require air delivery. The Operational Energy team visited over 50 locations across Afghanistan and completed assessments to evaluate and install improvements to power capabilities. These site assessments included material and nonmaterial recommendations to right-size tactical electric grids, operator training to maintain the grids, and insertion of energy storage and/or renewables to further reduce fuel consumption. The net effect was not just greatly reduced fuel, but also greater energy security and reduced human-power. Energy effectiveness is a force multiplier. Personnel that once refueled generators and moved fuel were freed up for other tasks.

More information:
https://apps.dtic.mil/dtic/tr/fulltext/u2/a622120.pdf.

Reusing Existing Natural Energy from Wind and Solar (RENEWS) and Renewable Energy for Distributed Undersupplied Command Environments (REDUCE)
Starting in 2009, the Army Communications–Electronics Research, Development and Engineering Center (CERDEC) developed a prototype wind-solar-battery hybrid power system for mobile missions supporting primarily communications systems like radios and laptops. The systems weighed around 100 pounds total and were designed to power up to three laptops continuously. Two systems were eventually field tested at Fort Irwin, and another was sent to African Command. The REDUCE program was complementary to RENEWS, focusing more on the microgrid systems and plug-and-play compatibility across components.

More information:

https://www.defencetalk.com/army-deployable-renewable-energy-solutions-42463/.

Deployable–Renewable Energy Power Systems (D-REPS)

In 2008, the U.S. Army Corps of Engineers contracted the services of SkyBuilt Power to develop and demonstrate two Deployable–Renewable Energy Power System (D-REPS) designs. Initially, the D-REPS were to be used at the National Training Center's forward operating base (FOB) in Miami. This off-grid power solution used the ample supply of the Mojave Desert's solar radiation and high winds to produce electricity and minimize the use of a backup fossil-fuel generator. These systems are designed to provide up to 7 kW of power for various Army tactical electrical loads, which are included in the National Training Center training mission. Each D-REPS includes 5 kilowatts-peak (kWp) of solar array, 80 deep-cycle batteries (totaling 1,000 amp-hours at 48 volts DC), a 900-watt wind turbine, two 3.5-kW inverters (DC-to-AC), and a backup 7.5-kW propane generator. One of the D-REPS was designed to fit inside an easily transportable, standard 20-foot shipping container, and the other was trailer-mounted. Both units were installed, operational, and providing performance data by the summer of 2008. In the spring of 2009, the shipping container D-REPS was moved from FOB Miami to an area called Moose Gardens, illustrating the versatility of the system. To date, the propane generators have only been brought online for testing procedures; the solar array and wind turbines have sufficed as the only sources for maintaining the charge on the battery bank, which ultimately provides power to the loads through the inverters.

More information:
https://erdc-library.erdc.dren.mil/jspui/bitstream/11681/14054/1/CERL-SR-10-7.pdf.

Existing Deployable Photovoltaic Systems

Unlike wind turbines, there is a large selection of deployable photovoltaic systems with a variety of sizes and configurations designed for a wide array of uses. Some specific example of adoption by DoD are listed below:

- Air Force Research Laboratory tested monocrystalline solar panels on top of tents that were integrated into a trailer-mounted microgrid in 2016 [14]. The project was to test feasibility of integrating a deployable power system into an FOB as part of an initiative to have a totally deployable, self-sustaining power system.
- The Dutch military has deployed thin-film solar systems in Afghanistan, and more recently in Mali [15]. In Mali, their system is a 100% deployable power unit that combines storage, solar, and diesel. Although the system has two 250-kW generators, the majority of the power comes from the flexible thin-film solar panels.
- The U.S. Army upgraded a surveillance system at the start of 2014, and part of the upgrade was integrating an alternative energy system to improve reliability and increase autonomy when deployed in remote, off-grid locations [16]. The energy system the U.S. Army deployed as part of the upgrade includes 16.8 kWh of energy storage, a 2.7-kW solar array, and the capability to automatically start and stop the 5-kW Tactical Quiet Generator (TQG).
- A U.S. Army research team, along with foreign soldiers, tested a human-portable, rucksack-born solar system in 2016 [17]. It was found that the system performed well during the exercise and could reduce the logistical burden of carrying batteries during missions.
- Although not necessarily deployable solar, there are over 400 megawatts of solar generation spread across domestic military bases [18] with future goals of increasing that amount. These prior projects offer an opportunity for lessons learned when deploying solar.

REFERENCES

[1] B. Naughton, R. Preus, and B. Whipple. 2020. *Market Opportunities for Deployable Wind Systems for Defense and Disaster Response*. Albuquerque, NM: Sandia National Laboratories. https://www.energy.gov/sites/default/files/2020/02/f71/deployable-turbine-market-assessment.pdf

[2] U.S. Department of Defense. 2019. *Environmental Engineering Considerations and Laboratory Tests (MIL-STD-810H)*. Arlington, VA: U.S. Department of Defense.

[3] U.S. Department of the Army. 2013. *Army Techniques Publication (ATP) 4-12, Container Operations*. Arlington, VA: U.S. Department of the Army.

[4] U.S. Department of the Army. 1999. *Cargo Specialists' Handbook (FM 55-17)*. Arlington, VA: U.S. Department of the Army.

[5] United States Air Force. 2017. *Preparing Hazardous Materials for Air Shipment (AFMAN24-204)*. Arlington, VA: United States Air Force.

[6] Institute of Electrical and Electronics Engineers. 2018. I*EEE Std 1547-2018: IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*. Piscataway, NJ: IEEE. https://sagroups.ieee.org/scc21/standards/1547rev/

[7] Institute of Electrical and Electronics Engineers. 2017. *IEEE Standard for the Specification of Microgrid Controllers*. Piscataway, NJ: IEEE https://standards.ieee.org/standard/2030_7-2017.html

[8] U.S. Department of the Army. 2018. *Soldier's Manual and Trainer's Guide Tactical Power Generation Specialist MOS 91D*. Arlington, VA: U.S. Department of the Army.

[9] International Organization for Standardization. 2020. *ISO 668:2020 Series 1 freight containers — Classification, dimensions and ratings*. Geneva, Switzerland: ISO.

[10] World Bank. 2019. "Global Wind Atlas." https://globalwindatlas.info/

[11] H. L. Wegley, J. V. Ramsdell, M. M. Orgill, and R. L. Drave. 1980. *A Siting Handbook for Small Wind Energy Conversion Systems*. Richland, WA: Pacific Northwest National Laboratory. https://doi.org/10.2172/5490541

[12] T. Olsen and R. Preus. 2015. *Small Wind Site Assessment Guidelines*. Golden, CO: National Renewable Energy Laboratory. https://doi.org/10.2172/1225476

[13] J. F. Manwell. 2010. *Wind Energy Explained*. West Sussex, UK: John Wiley & Sons Ltd.

[14] D. Lindner. 2017. "Air Force Develops New, Deployable Energy Systems." U.S. Department of Defense, April 6, 2017. https://www.defense.gov/Explore/News/Article/Article/1143863/air-force-develops-new-deployable-energy-systems/

[15] EST-Floattech. 2020. "World's First Military 100% electric Deployable Power Unit." https://www.est-floattech.com/

[16] Solar Stik. 2018. "Solar Stik®, Inc. Ships 100th Hybrid Power System 700 to the U.S. Army." https://www.solarstik.com/solar-stik-inc-ships-100th-hybrid-power-system-7000-to-the-u-s-army/.

[17] D. Lafontaine. 2016. "Army deonstrates rucksack power, enhances translation research in African exercise." U.S. Army, July 21, 2016. https://www.army.mil/article/171982/army_demonstrates_rucksack_power_enhances_translation_research_in_african_exercise

[18] P. MacDonald. 2019. "U.S. Military Solar Power Jumps Up-Significantly." *energy Magazine*, Winter 2019. https://www.altenerg.com/back_issues/story.php?sid=1714

This page left blank