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# **Atmospheric Renewable Energy Research, Volume 3: Solar-Power Microgrids and Atmospheric Influences**

**by Gail Vaucher, Morris Berman, and Jeffrey A Smith**

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# **Atmospheric Renewable Energy Research, Volume 3: Solar-Power Microgrids and Atmospheric Influences**

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## Contents

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<b>List of Figures</b>	<b>v</b>
<b>Acknowledgments</b>	<b>vi</b>
<b>Executive Summary</b>	<b>vii</b>
<b>1. Introduction</b>	<b>1</b>
1.1 Supportive Renewable Energy Policies and Directives	1
1.2 DOD Renewable Energy Applications	1
1.3 Atmospheric Renewable Energy Research Strategy	2
1.4 Microgrid Definitions	3
1.4.1 Mobile Microgrid	4
1.4.2 Hybrid Microgrid	4
1.4.3 Smart Microgrid	4
1.5 Long-Term Atmospheric Renewable Energy Research Vision	5
<b>2. Atmospheric Dependencies</b>	<b>5</b>
2.1 Sun4Cast	6
2.2 Watt-Sun	7
<b>3. Hybrid Power Grid Analysis</b>	<b>7</b>
<b>4. Power Grid Ramping Events</b>	<b>9</b>
<b>5. Microgrid Simulation</b>	<b>9</b>
5.1 Microgrid Simulation Design	10
5.2 Microgrid Simulation Input	11
<b>6. Summary and Conclusions</b>	<b>12</b>
<b>7. References</b>	<b>14</b>
<b>List of Symbols, Abbreviations, and Acronyms</b>	<b>16</b>



## List of Figures

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Fig. 1	March 22, 2014 solar irradiance time series on a partly cloudy day in a southwestern USA desert environment.....	9
Fig. 2	A microgrid 3-tiered configuration.....	10

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## Executive Summary

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Saving lives, strengthening security, and improving economics motivate the US Army Research Laboratory (ARL) to investigate the integration of renewable energy into Department of Defense (DOD) and military missions. Replacing just 1% of the Armed Forces' Operational Energy fossil fuel with renewable energy resources has a significant impact: less fuel convoys reduces Soldier risks; the power source diversity fortifies security; and the renewable nature of the resource diminishes cost requirements.

Renewable energy integration requires a variety of disciplines (power engineers, mechanical engineers, meteorologists, physicists, etc.). Establishing common definitions and understandings are a critical cornerstone for this joint investigation. In Volume 1,<sup>1</sup> we documented the various contemporary commitments by the US Government/DOD/Armed Forces toward actively integrating renewable energy into their respective missions. In Volume 2,<sup>2</sup> we set a cornerstone by researching the components of solar-power system designs with a focus on atmospheric contributions. In Volume 3, we begin building on the cornerstone by investigating the challenges associated with combining multiple power systems together, creating an integrated microgrid. Looking toward the future, we envision the not-yet-developed-for-Army “smart” mobile hybrid microgrid that will incorporate both traditional and renewable energy power resources.

A significant hurdle in the path of successfully operating this hybrid (solar/diesel) microgrid is ensuring smooth transitions between traditional and nontraditional power resources. This barrier was investigated from 3 perspectives. We 1) identified atmospheric dependencies associated with the hybrid microgrid, 2) explored basic power grid models and ramping events—one of the most vulnerable solar microgrid functions associated with atmospheric conditions, and 3) examined microgrid tools that will assist in resolving atmospheric-dependent vulnerabilities and opportunities.

In Section 2, atmospheric parameters impacting the solar-power generation are defined and contemporary atmospheric renewable energy forecast models presented. First hand experiences gained in validating the solar-power design (Volume 2) confirmed the atmospheric dependencies identified. In Sections 3 and 4, a basic power grid model is presented, along with foundational information

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<sup>1</sup>Vaucher G. Atmospheric renewable-energy research, Volume 1 (background: “to be or not to be”). White Sands Missile Range (NM): Army Research Laboratory (US); 2015 Sep. Report No.: ARL-TR-7402.

<sup>2</sup>Vaucher G. Atmospheric renewable energy research, Volume 2: assessment process for solar-powered meteorological applications. White Sands Missile Range (NM): Army Research Laboratory (US); 2016 Aug. Report No.: ARL-TR-7762.

regarding one of the most vulnerable hybrid grid functions associated with atmospheric conditions, namely “ramping events”. Section 5 presents the nontrivial microgrid simulation design and input options. Through the use of microgrid simulations and atmospheric renewable energy research, we can identify hybrid microgrid “scenarios of interest” (vulnerabilities and opportunities). By quantifying the atmospheric-dependent impacts, the ongoing investigation is poised to pursue the development of microgrid “smart tools” to mitigate the negative consequences and exploit the positive atmospheric impact opportunities.

## **1. Introduction**

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Saving lives, strengthening security, and improving economics compel the US Army Research Laboratory (ARL) to investigate the integration of renewable energy into Department of Defense (DOD) and military missions. When the Armed Forces move around the globe, they must transport all their power resources. These resources include liquid fuels, which become a serious vulnerability when they are convoyed between locations. Any process that reduces the targeted assets, give Soldiers a decisive edge over their counterparts (by keeping more US Soldiers alive to face another day). The integration of renewable energy resources into traditional operational energy applications is just one method that will accomplish this objective (US Army 2010). The use of renewable energy with traditional power resources also provides a diversity of power and a smaller footprint of flammable hazardous materials at forward operating bases (FOBs) in theatre. The quiet nature of solar energy means one less identifiable signature for mobile military units; thus, security is improved. With less fossil fuel consumed due to natural replenishing of renewable sources, economic saving increases (The Pew Charitable Trust 2011). Until renewable resources are fully developed and integrated into tactical environments, realizing the economic savings quantitatively is subjective, but still logical.

### **1.1 Supportive Renewable Energy Policies and Directives**

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The field of renewable energy gained a significant boost in the early 2000s, when Congress passed Public Law 109-58 Energy Policy Act of 2005 (US Congress 2005) and the DOD initiated their 10-year DOD Directive No. 4180.01, which centered on enhancing military capabilities (saving lives), improving energy security and mitigating costs in energy usage and management (DOD Issuance 2015). Each of the Armed Forces published commitments toward the integration of renewable energy into their individual missions. For more information on these topics and other policies, see Volume 1 (Vaucher 2015).

### **1.2 DOD Renewable Energy Applications**

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The ARL atmospheric renewable energy research began with a survey of renewable energy products being integrated into military missions. In 2015, the pioneering results were grouped into 3 categories:

- Large scale (>10 MW): Utility/Installation applications.
- Medium scale (1–40 MW): Microgrids.

- Small scale (<1 MW): Tactical applications.

The distinguishing attributes of each classification included the following:

- Large-scale applications were primarily employed at permanent military bases.
- Medium-scale applications were designed for semi-fixed, large theatre bases.
- Small-scale applications were considered “mobile”.

Since the provision of these definitions, new technologies have surfaced creating building blocks toward a future mobile hybrid (solar/diesel) microgrid. The current new product attributes carry elements of both the medium- and small-scale applications. Consequently, for this research we will temporarily combine the medium- and small-scale groups until the developing technologies again distinguish the categories.

### **1.3 Atmospheric Renewable Energy Research Strategy**

Renewable energy research requires a diverse team of professional disciplines, such as power engineers, mechanical engineers, meteorologists, physicists, and so forth. To optimize communications between these professions, we began this joint research with a clarification of foundational definitions and understandings. In Volume 1 (Vaucher 2015), we documented the various contemporary commitments by the US Government, the DOD, and the various Armed Forces toward actively integrating renewable energy into their respective missions. In Volume 2 (Vaucher 2016), we set a cornerstone by studying the components of solar-power system designs, with a focus on atmospheric contributions. In Volume 3, we begin building on the cornerstone by investigating the challenges of joining multiple power resources and systems together into an integrated microgrid. Between Volumes 2 (Vaucher 2016) and 3, we physically constructed a solar-power system, and acquired multiple atmospheric measurement sets to test our understanding. We also conversed with numerous grid and microgrid engineers concerning various elements of their profession.

One method for integrating renewable energy into the military mission is to develop a hybrid (solar/diesel) microgrid. A significant hurdle in the path of successfully operating such a hybrid microgrid is ensuring smooth transitions between traditional and non-traditional power resources. To pass this barrier, we investigated the issues from 3 perspectives. We 1) identified atmospheric dependencies, 2) examined studies done regarding power transitions (ramping

events), and 3) examined various tools that could assist in resolving the hurdle. In Section 2, atmospheric parameters impacting the solar-power generation are defined and contemporary atmospheric renewable energy forecast models presented. Experiences gained in validating the solar-power design (Volume 2) (Vaucher 2016) confirmed the atmospheric dependencies identified in this section. In Sections 3 and 4, basic power grid models and studies regarding power ramping are summarized. Microgrid simulations, their design and data input, are described in Section 5.

Pioneering atmospheric renewable energy research for military applications has presented several gray areas, which is why we now clarify terms that will be key to the technical material presented.

#### **1.4 Microgrid Definitions**

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There are currently several definitions for a microgrid. From literature and personal communications, we found that most definitions were a function of their application. If the power application was associated with a utility grid, one of following 4 microgrid types might be given: “Customer Microgrids”, “Utility Microgrids”, “Virtual Microgrids”, and “Remote Microgrid”. A description of each follows:

- “Customer Microgrids” or “True Microgrids” ( $\mu$ grids):  $\mu$ grids are self-governed systems that are usually downstream of a single point of common coupling and their power system operation is generally given considerable independence (Types of Microgrid 2015).
- “Utility”, “Community” or, “milligrids” (mgrids): mgrids involve a segment of a regulated grid and incorporate traditional utility infrastructure (i.e., the mgrid complies with existing utility codes and standards) (Types of Microgrid 2015).
- “Virtual Microgrids” (vgrids): Vgrids cover distributed energy resources at multiple sites, but are coordinated so that the grid recognizes them as a single controlled entity. The system must be able to operate as a controlled island or coordinated multiple islands. Very few vgrids exist, according to Berkeley Lab (Types of Microgrid 2015).
- “Remote power system grid” (rgrids): Rgrids are not grid-connected. These isolated power systems involve similar, closely related technologies. From a research perspective, they are commonly described as microgrids. Rgrids come the closest to describing the mobile hybrid microgrid referenced in this research (Types of Microgrid 2015).

The Department of Energy (DOE) defined a microgrid as:

“...a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island-mode” (DOE Microgrid Workshop Report 2011).

For this research, our microgrid definition is very similar to the DOE description. We define it as multiple power resources assembled as a single system (generation, storage, distribution, and load), with the ability to run independently as an “island”, and/or, as an integrated part of a larger grid. The subtle difference will become evident as we expand our terms in the next few sections.

#### **1.4.1 Mobile Microgrid**

Mobile microgrids are self-contained power grids that can generate, store, and distribute electrical energy, and function as isolated units, yet are also able to feed electricity to a larger power grid. Based on the current state of evolving technology, we blend the microgrid and tactical scale grid attributes, to further describe this category as semi-fixed, transportable, dynamic, flexible, able to function for unknown durations (hours to months), and can be a hybrid of renewable and nonrenewable electrical-generating resources. When operating for short durations, they may have limited alternative energy (battery) and be of a plug and play nature—used for specific functions with a known load. The smaller, “personal scale” grid power is generally very reliable and more easily maintainable than larger scale systems.

#### **1.4.2 Hybrid Microgrid**

A hybrid microgrid is one that integrates multiple power type resources. These power types can include traditional fossil fuel power generating resources, as well as the nontraditional renewable energy power resources such as solar, wind, geothermal, and so forth. For this research, the “hybrid” referenced will incorporate solar battery(ies) and traditional fossil fuel power generating resources.

#### **1.4.3 Smart Microgrid**

Looking toward the future, we include the term, “smart” microgrid. Extracting the concept from the larger “smart” utility power grids, a smart microgrid is defined as a microgrid that uses 2-way communications for providing power, measuring variations in load demands, and automatically adjusting electrical distribution and loads to match the available power.

## **1.5 Long-Term Atmospheric Renewable Energy Research Vision**

The long-term vision for this research is to build tools useful to the future, smart, mobile, hybrid microgrids so that they will gain a significantly higher efficiency, once their smart elements successfully integrate both “live” and predicted atmospheric conditions into their decision making processes.

In Section 2, solar-powered renewable energy atmospheric dependencies are presented.

## **2. Atmospheric Dependencies**

The strongest atmospheric dependency for solar-power is solar radiation. For maximum solar-power production, one ideal atmospheric/environmental scenario consists of the following: no clouds, minimal aerosols, and a maximum ambient (panel) temperature of 25 °C. The solar photovoltaic (PV) panel would be mounted on a pole, and for maximum solar energy input, would track the sun’s progress through the sky using a panel azimuth and elevation that keeps the sun’s rays orthogonal to the plane of the panel.

Unfortunately, the equipment used to track the sun can be expensive and requires electrical power. To minimize cost and power consumption, solar-power designers often use averaged azimuth and elevation angles for the panel orientation. This choice presumes the power system design is not constrained by other local environmental factors, which will be addressed later.

The 25 °C temperature was selected based on the conditions required to measure a PV panel’s “peak power”. This peak power quantity is used by marketers, to describe PV panels for inter-panel comparison purposes. From Boxwell (2013), for every 1 °C above (or below) this calibration point, the solar-power system will lose (or gain) a 0.5% efficiency.

The optimal solar radiation can be impacted by both hard and soft shadowing. The hard shadowing (building shadows, growing foliage, fallen branches, fowl refuge, etc.) is generally addressed through manually moving the PV panel to an alternative location, trimming nearby foliage, or cleaning the PV surface.

Soft shadowing (clouds and aerosols) reduces the solar-power opportunity of the PV, and has been the subject of much research. While detailing all the ongoing research done in solar-power forecasting is beyond the scope of this report, what follows are highlights from 2 recently completed DOE-sponsored, research programs: Sun4Cast and Watt-Sun.

## 2.1 Sun4Cast

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From 2013 to 2016, the “Advance Solar Power Forecasting Project” (also known as SunCast and Sun4Cast) was pursued by a consortium of national laboratories, universities, industry partners, forecast providers, utility companies across the United States, and Independent System Operator (ISO) balancing authorities. The underlying goal of this University Corporation for Atmospheric Research (UCAR)-led project was to develop short-term cloud prediction techniques, based on observations.

Sun4Cast used a 2-pronged approach that coupled observation data with various short-range Nowcasting (0–3 h) and medium-range Numerical Weather Prediction (NWP) (~3 to 48 h) forecasting models. The 4 Nowcast models investigated consisted of the following: Statistical Forecast (StatCast), Total Sky Imager Forecast (TSICast), Cooperative Institute for Research in the Atmosphere Forecast (CIRACast), and Multi-sensor Advection Diffusion foreCast (MADCast). Nowcast results were blended with the NWP model output, including Weather Research and Forecasting (WRF)-Solar Model. A prediction uncertainty was determined by the Analog Ensemble forecast (AnEn). AnEn integrated similar historical scenarios into results for comparison. Utility partners worked with the Sun4Cast Team, guiding the forecasting priorities and testing the final forecasting tool.

The project results, which are open source, advanced methods for measuring solar radiation, observing clouds, executing high-resolution Nowcasts, and quantifying/tracking aerosols, haze, and contrails (which impact cloud formation).

Some of the solar-power forecasting recommendations included the following (Haupt 2016):

- Forecasts were significantly better when produced from blended models / systems versus a single model or approach. This characteristic was especially noted for NWP models forecasting for 3 h through day-ahead forecast and beyond.
- Significant improvements were observed when using a NWP model tuned for a specific purpose, such as WRF-Solar.
- Persistence forecasts can be improved for very short-range by using methods trained on targeted in situ observations. For example, StatCast trained to utilize pyranometer data was better than persistence at short timescales of 15 min to 3 h. Also, TSICast using multiple sky imagers, improved upon persistence in the time range of less than 15 min.



- Satellite-based cloud advection for regions near the mountains or along coasts needed model physics to account for stationary clouds and cloud development. Also, correcting for shadowing and parallax was important to the CIRAcast.
- NWP combined with assimilated satellite data produced a fast-running, short-range (0–6 h) forecast that was helpful for Nowcasting; this method produced the best 1–6-h timescale forecast.
- The AnEn method improved the deterministic blended forecast and helped in producing a probabilistic prediction.
- An empirical power conversion method was responsive to training site-specific information, in data sparse areas. With historical training data, artificial intelligence techniques can predict directly from observations.
- Enhanced metrics helped in evaluating and tuning individual models as well as entire systems.
- The utility’s need for solar forecasting was persistent and will only get larger as more distributed energy is connected to the grid.
- Future forecasting logistics will be from a centralized location with multiple uses and at varying granularity of details.

## 2.2 Watt-Sun

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Coincident with the Sun4Cast effort, the International Business Machines Corporation (IBM) led a DOE-sponsored collaboration (Watt-Sun) aimed at bringing powerful computers to the large data processing of NWP models and state-of-the-art machine learning technologies that determined solar installation output. IBM Research Manager Hendrik Hamann stated, “Solar and wind forecasts produced by IBM’s technology are as much as 30% more accurate than conventional forecasts” (Martin 2015). Hamann also recognized that no NWP model is perfect, and results at best make approximations.

In the following sections, we focus on the other major component of this research: power grids.

## 3. Hybrid Power Grid Analysis

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For a power grid, power generated (source) must equal power consumed (demand). Expressed mathematically, a hybrid microgrid would be,

$$G + B + R = L + S + D, \tag{1}$$

where the source (supply) is

G: Grid-supplied Power—Power generated by fixed local generation capacity,

B: Battery Power—Power supplied by a storage capacity, and

R: Renewable Energy Power—Power from components such as wind and solar;

and the demand (load) is

L: Load Consumption—Power consumed by load, i.e., lights, computers, and so forth,

S: Storing Power—Power stored (recharging batteries), and

D: Dissipated Power—Power dissipated or lost due to conversion and transport.

Renewable energy is a challenge for power generation because unlike the typical demand that behaves in a predictable stochastic manner, renewable energy sources are highly variable and to some degree less predictable. From a utility company perspective, the variability of renewable sources is manageable as long as these sources represent a “small fraction” of the power requirements. For the WestConnect system, where WestConnect is “a group of transmission providers that are working collaboratively on initiatives to improve wholesale electricity markets in the West”, this fraction could be as much as 35% of the generation needs without significant changes in grid architecture or management (Lew et al. 2010).

For customer/true microgrids or isolated rgrids, the challenge of renewable energy is much greater. Pascual et al. (2015) notes 2 basic configurations for these grids. In the first configuration, the model becomes

$$B + R = L + S + D, \quad (2)$$

where the entire source of power comes solely from battery and the renewable component. In this case, the main task is to manage the demand side of the equation so that the batteries do not become depleted. In the second configuration, the model is as Eq. 1:

$$G + B + R = L + S + D. \quad (3)$$

Here the G represents solely the local generation capacity. Pascual et al. (2015) notes that this second case is similar to a grid-tied system in the sense that the grid can act both as a sink and a source for excess power, wherein the grid takes on the roles of S and B, respectively, in Eq. 3. The main task in this case becomes both one of load management and optimization of the local generation capacity to minimize “cost” of operation.

## 4. Power Grid Ramping Events

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Kamath (2010) and Florita et al. (2013) refer to the changes in either the source of, or demand for, power as a “ramp event”. For utility-based systems, these ramp events are stochastic processes with established mechanisms for handling them. For renewable systems, ramp events can be quite “spikey” (see Kamath 2010, Figure 2) exhibiting both day-to-day, diurnal, and cloud cover effects. Figure 1 demonstrates an equivalent spikey power time series, as quantified by solar radiation data during a partly cloudy day, in a desert environment. From a system control point of view, this spikey behavior becomes a problem because rapid changes can lead to undesirable issues such as over- and under-voltages that can damage equipment. A simple method for dealing with this behavior is to smooth the generation curve with a low pass filter or to approximate it with a piecewise linear curve between inflection points (Kamath 2010; Florita et al. 2013). With such a construction, it becomes possible to estimate the expected available renewable energy over some appropriate interval of time, and switch on or off generation capacity, as needed. A more ideal approach is to introduce atmospheric forecast estimates into the control system, which is a long-term goal of this research.

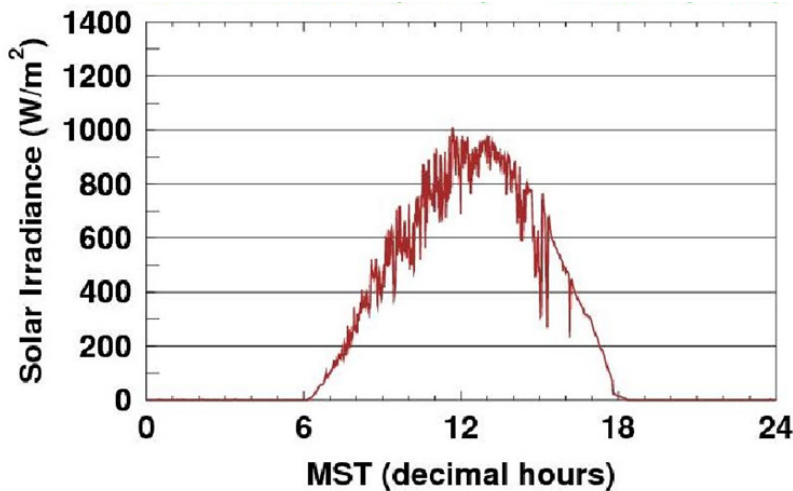


Fig. 1 March 22, 2014 solar irradiance time series on a partly cloudy day in a southwestern USA desert environment

## 5. Microgrid Simulation

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Without a physically available (nor constructed) hybrid microgrid to examine and test, this research relied on ARL’s ability to simulate a microgrid. The simulation design and executions were a joint research venture by ARL and Michigan Technological University (MTU). As with all new horizons, the first major

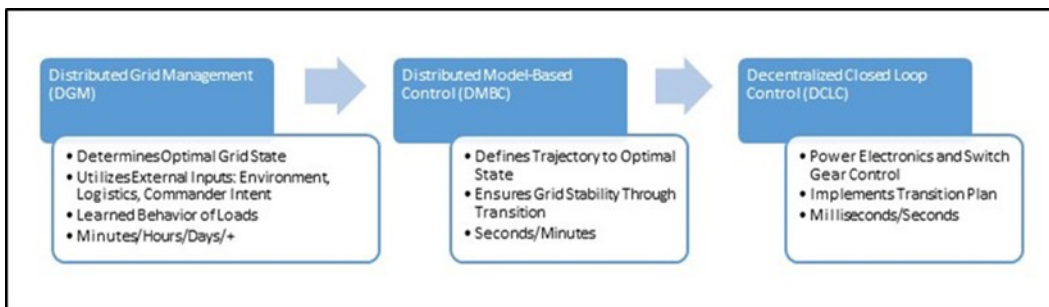
milestone was to successfully establish the tool and technology critical to the research. ARL and MTU achieved this goal.

In the following sections, we describe the microgrid simulation design and input data (focusing on atmospheric data), as required for simulating grid operations.

## 5.1 Microgrid Simulation Design

The microgrid simulation was developed based on MTU’s Agile Autonomous Microgrid (AAM) controller technology. The AAM was successfully demonstrated on a discrete event simulator running in a MATLAB environment. The AAM controller was implemented on an Opal-RT hardware-in-the-loop (HIL) system at ARL’s Tactical Energy Network Research Facility (TEN-RF) at the Adelphi Laboratory Center, Maryland.

The AAM consisted of a 3-tiered agent-based design that controlled the overall grid configuration down to various loads, such as closed-loop controllers for heating, ventilating, and air conditioning (HVAC) systems, radars, dining facilities, and so forth. The top level of the system, the Distributed Grid Management (DGM), controlled the overall grid configuration. The middle tier, the Distributed Model Based Control (DMBC), was responsible for implementing the configuration imposed by the top-level DGM. The lowest tier, the Distributed Closed Loop Control (DCLC), was responsible for controlling individual components as per the midtier DMBC instructions. Figure 2 summarizes this 3-tier configuration and their functions.



**Fig. 2 A microgrid 3-tiered configuration**

Each tier operated with different inputs and at different timescales. The DGM (top layer) primarily took its input from external stimuli. Some examples of these events/conditions include anticipated fuel deliveries, near-term or far-term mission requirements, known arrival/departure of energy resources such as vehicles, and weather. Using these inputs, as well as the priorities of the known resources and loads on the grid, the DGM computed a new power schedule and coordination schema. The DGM operated at timescales of minutes through days. For instance,

one boundary condition imposed on the DGM might be that “there will be no fuel deliveries for the next seven days while there is an upcoming mission in the next two days that will require charging three hybrid vehicles to a full battery charge”. For this case, the DGM would compute a new power schedule and coordination schema, based on the new conditions. The configuration would involve load shedding or minimizing the use of storage and renewable resources.

The DGM also computed a power schedule and coordination schema as time passed, and new and/or better information became available. For instance, the weather predictions and fuel usage predictions might become more accurate as the time horizon decreases, so the optimal grid configuration would also vary. Another example of time-impacted conditions is inserting command input that could change as mission requirements evolved.

Once a new grid configuration was computed, the configuration was passed to the DMBC. The DMBC determined how to implement the solution, and optimized the grid set-points to ensure that the networked microgrid was optimized in regard to a given parameter such as fuel usage, fire power, security, and so forth. The DMBC provided input to each resource and load that would result in the desired end-state. The DMBC was also responsible for ensuring that the glide-slope to the target state did not destabilize the networked microgrid. For instance, if the end-state required several HVAC units to start, the DMBC ensured that the proper energy resources were available prior to activating those loads. The DMBC was also responsible for implementing the solution within the time frame specified by the DGM. The DMBC operated on a timescale of seconds to minutes. The DMBC defined the state of individual loads at a particular point in time and passed that information to the load’s DCLC when one was present.

While certain loads will not implement a DCLC component, inclusion of the DCLC enabled a more optimized grid solution. For instance, if an HVAC unit incorporated a DCLC controller, the DMBC could ensure that multiple compressors do not start simultaneously. Additionally, in the case of an HVAC controller, the DCLC could control not only the set-point temperature of the system, but also the allowable temperature range. Power electronics and automated switchgear could implement a DCLC controller. This flexibility provided a much larger number of degrees of freedom to the overall grid control algorithm resulting in more optimal solutions. (Weaver et al. 2016)

## **5.2 Microgrid Simulation Input**

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Once the AAM is properly implemented on the Opal-RT HIL system, the AAM can be exercised in a variety of ways to explore the impact of meteorological

predictions. The initial scenario implemented for the AAM was the Dynamo II dataset. This dataset defined a typical series of events and their associated loads in a military base. Another dataset obtained by ARL during this research effort was from the 2016 Base Camp Integration Laboratory (BCIL) Demonstration. The BCIL data included detailed load and source data as well as ARL's coincident solar irradiance, Simulated-Whole Sky Imager (s-WSI) and meteorological sky observation data.

In future simulations, atmospheric predictions (forecasts) with various time-horizons (hours- to days-ahead) will be developed based on the collected meteorological data. These predictions, as well as the current measured atmospheric state data, will then be provided to the DGM, in real time, resulting in a particular set of grid performance parameters. Separate grid simulations will be executed that include no meteorological predictions, as well as predictions at specific time horizons with a specified accuracies. By comparing the grid performance under the varied prediction parameters, an assessment of the value-added by the meteorological predictions will be developed. Two simulation cases where current and foreknowledge of weather conditions is anticipated to have a significant impact on microgrid operations involve the atmospheric effects on PV power generating sources, and the weather's impact on grid customer HVAC usages. Through the use of microgrid simulations and atmospheric renewable energy research, we look forward to not only identifying the "scenarios of interest", but quantifying the impacts, and developing microgrid "smart" tools to mitigate the negative consequences and exploit the positive impact opportunities.

## **6. Summary and Conclusions**

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The integration of renewable energy into DOD and military missions can save lives, strengthen security, and improve economics. Reducing the Armed Forces' Operational Energy fossil fuel consumption with renewable energy resources by just 1% has a significant impact. This impact stems from a reduced number of required fuel convoys (saving Soldier lives), providing a diversity of power (strengthening security) and with the renewable nature of the resource, shrinking cost requirements.

A diversity of professional disciplines (power engineers, mechanical engineers, meteorologists, physicists, etc.) are needed to support renewable energy integration. To optimize coherent communications, establishing common definitions and understandings are a critical cornerstone. In Volume 1 (Vaucher 2015), we documented the various current commitments by the US Government and Armed Forces toward actively integrating renewable energy into their

respective missions. In Volume 2 (Vaucher 2016), we set a keystone by researching the components of solar-power system designs, with a focus on atmospheric contributions. In Volume 3, we built upon the foundation by investigating the challenges associated with combining multiple power systems together to create an integrated hybrid microgrid. Looking toward the future, we visualize a not-yet-developed-for-Army mobile hybrid microgrid, which would incorporate both traditional and renewable energy power generations.

A significant barrier in the path of successfully operating a hybrid (solar/diesel) microgrid is ensuring smooth transitions between traditional and nontraditional power resources. This technical challenge was investigated from 3 angles. We 1) identified atmospheric dependencies associated with the hybrid microgrid, 2) explored basic power grid models and power ramping—one of the most vulnerable microgrid functions associated with atmospheric conditions, and 3) examined microgrid simulation tools aimed at defining and resolving the atmospheric-dependent vulnerabilities and opportunities.

Solar radiation and temperature were 2 atmospheric parameters that significantly influence solar-power generation. In Section 2, we elaborated on these parameters and their impact. We also described current, relevant atmospheric renewable energy forecast models being developed. Experiences gained in validating the Volume 2 (Vaucher 2016) solar-power design, confirmed the identified atmospheric dependencies. In Sections 3 and 4, a basic power grid model was presented, along with foundational information regarding one of the most vulnerable hybrid grid functions associated with atmospheric conditions, namely “ramping events”. Section 5 presented the design and research-relevant input options for microgrid simulations. The next step in this research will be to investigate the designing of a solar/diesel management tool.

Through the use of microgrid simulations and atmospheric renewable energy research, we can now identify hybrid microgrid “scenarios of interest” (vulnerabilities and opportunities). By quantifying the atmospheric-dependent impacts, the ongoing investigation is poised to pursue the development of the future microgrid “smart tools” (solar/diesel management tool) to mitigate the negative consequences and exploit the positive atmospheric impact opportunities.

## 7. References

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- Boxwell M. Solar electricity handbook, 2013 edition, a simple, practical guide to solar energy—designing and installing photovoltaic solar electric systems. Ryton on Dunsmore Warwickshire: Greenstream Publishing (UK); 2009–2013.
- DOD Issuances: The Official Department of Defense Website for DOD Issuances. [accessed 2015 May 14]. <http://www.dtic.mil/whs/directives>.
- Florita A, Hodge B-M, Orwig K. Identifying wind and solar ramping events. IEEE Green Technologies Conference; 2013 Apr 4–5; Denver (CO). p. 147–152. doi: 10.1109/GreenTech.2013.30.
- Haupt SE, Branko K, Jensen T, Lee J, Jimenez P, Lazo J, Cowie J, McCandless T, Pearson J, Weiner G, et al. The SunCast™ solar-power forecasting system: the results of the public-private-academic partnership to advance solar power forecasting. National Center for Atmospheric Research (NCAR), Boulder (CO): Research Applications Laboratory, Weather Systems and Assessment Program (US); 2016. NCAR Technical Note: NCAR/TN-562+STR.
- Kamath C. Understanding wind ramp events through analysis of historical data. 2010 IEEE PES T&D, 1–6. doi: 10.1109/TDC.2010.5484508.
- Lew D, Piwko D, Miller N, Jordan G, Clark K, Freeman L. How do high levels of wind and solar impact the grid? The western wind and solar integration study. National Renewable Energy Laboratory, Golden (CO); Dec 2010. Technical Report: NREL-TP-5500-50057.
- Martin R. Solar and wind forecasts are new wave of weather reporting. MIT Technology Review: 2015 July 21 [accessed 2015 July 28]. <http://mashable.com/2015/07/21/weather-forecasting/>.
- DOE Microgrid Workshop Report, 2011 Aug 30–31. Office of Electricity Delivery and Energy Reliability Smart Grid R&D Program: San Diego (CA) [accessed 2016 Sep 07]. <http://energy.gov/sites/prod/files/Microgrid%20Workshop%20Report%20August%202011.pdf>.
- Pascual J, Barricarte J, Sanchis P, Marroyo L. Energy management strategy for a renewable based residential microgrid with generation and demand forecasting. Applied Energy. 2015 Nov;158:12–25. doi: 10.1016/j.apenergy.2015.08.040.



- (The) Pew Charitable Trusts. From barracks to the battlefield: clean energy innovation and America's armed forces. 2011 Sep 21 [accessed 2015 May 26]. <http://www.pewtrusts.org/en/research-and-analysis/reports/2011/09/21/from-barracks-to-the-battlefield-clean-energy-innovation-and-americas-armed-forces>.
- Types of Microgrids, Microgrids at Berkeley Lab, Grid Integration Group, Energy Storage and Distributed Resources Division, US DOE, [accessed 2015 Oct 13] <https://building-microgrid.lbl.gov/types-microgrids>
- US Army. Stand-To!—Today's Focus: Army Operational Energy Strategy; 2010 July 26 [accessed 2015 Mar 10]. <http://www.army.mil/standto/archive/2010/07/26/>.
- US Congress 2005. Public Law 109–58, Aug 8, 2005. Energy policy act of 2005, [accessed 2016 Sep 12] <http://www.gpo.gov/fdsys/pkg/PLA-109publ58/pdf/PLAW-109publ58.pdf>.
- Vaucher G. Atmospheric renewable-energy research, Volume 1 (background: “to be or not to be”). White Sands Missile Range (NM): Army Research Laboratory (US); 2015 Sep. Report No.: ARL-TR-7402.
- Vaucher G. Atmospheric renewable energy research, Volume 2: assessment process for solar-powered meteorological applications. White Sands Missile Range (NM): Army Research Laboratory (US); 2016 Aug. Report No.: ARL-TR-7762.
- Weaver W, Robinett R, Parker G, Wilson D. Hamiltonian modeling and control of AC microgrids with spinning machines and inverters, 2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM); 2016 June 22–24; Anacapri, Italy; p. 150–155. doi: 10.1109/SPEEDAM.2016.7526027.

## List of Symbols, Abbreviations, and Acronyms

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AAM	Agile Autonomous Microgrid
AnEn	Analog Ensemble
ARL	US Army Research Laboratory
BCIL	Base Camp Integration Laboratory
CIRACast	Cooperative Institute for Research in the Atmosphere Forecast
DCLC	Distributed Closed Loop Control
DGM	Distributed Grid Management
DMBC	Distributed Model Based Control
DOD	Department of Defense
DOE	Department of Energy
FOB	forward operating base
HIL	hardware-in-the-loop
HVAC	heating, ventilating, and air conditioning
IBM	International Business Machines Corporation
ISO	Independent System Operator
MADCast	Multi-sensor Advection Diffusion foreCast
mgrids	milligrids
MTU	Michigan Technological University
NWP	Numerical Weather Prediction
PV	photovoltaic
rgrids	Remote power system grid
StatCast	Statistical Forecast
s-WSI	Simulated-Whole Sky Imager
TEN-RF	Tactical Energy Network Research Facility
TSICast	Total Sky Imager Forecast

UCAR	University Corporation for Atmospheric Research
Vgrids	virtual microgrids
WRF	Weather Research and Forecasting
μgrids	microgrids

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