IPOWER: A Dismounted Warfighter Energy Simulation and Analysis Tool

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Abstract: *The US Army and Marine Corps need a way to understand dismounted warfighter energy systems quantitatively to inform acquisitions and doctrine development. The U.S. Naval Research Laboratory (NRL) developed the IPOWER energy simulation tool to satisfy this need with quantitative analysis of dismounted warfighter missions and equipment in realistic environments. IPOWER combines step-wise state integration, nonlinear component models, and climate data with optimization algorithms and a simple user interface. Ease of use is key; it runs as a web app and users interact with it through a browser much like a website. IPOWER is currently distributed as a standalone application, but work is underway to make it widely available within DoD as a cloud service with CAC login.*

Keywords: energy; power; soldier; model; simulation; mission; optimize.

Introduction

Dismounted warfighters face constantly evolving challenges on the battlefield, and one way they meet those challenges is with new, more capable equipment. They rely on program offices, the research and development community, and industry to provide that new equipment. Unfortunately, it often comes with greater complexity and energy consumption. The modern warfighter is more capable, but the energy problem has grown to a point where their performance is hindered by the weight of batteries they must carry and the time they spend on energy management. Furthermore, the need for frequent energy resupply makes warfighters vulnerable to attack. This problem is forcing decision-makers to consider energy in the selection of new equipment and architectures for dismounted warfighters.

In the past, the only sources of energy information available to acquisition offices were rough approximations, anecdotal evidence, and field experiments with many uncontrolled variables. That made it difficult and time consuming (or even impossible) to compare options quantitatively and make decisions confidently. The Intelligent Power Optimization with Environmental Reactivity (IPOWER) simulation tool was developed to inform the acquisition process with fast, rigorous, and quantitative energy analyses.

IPOWER users set up a mission scenario (location and activity timeline), assign equipment to individuals and units, and then run the energy simulation. They can configure equipment models, mission activities, and unit structures based on templates in IPOWER. That flexibility enables them to base their analyses on existing equipment or incorporate hypothetical equipment to answer "what if" questions and guide development priorities. IPOWER provides results in the form of metrics, charts, plots, and other graphics that examine the scenario from different perspectives. Examples include the number of batteries required for the mission, the amount of fuel consumed, and the amount of energy harvested. Results can be exported to a spreadsheet for further analysis.

IPOWER users can simulate different scenarios in the same environment, or the same scenario with different equipment, to make apples-to-apples comparisons with a consistent baseline. IPOWER can help winnow candidate technologies early in the evaluation process and improve the chances that an expensive field-test will identify a winning solution.

Workflow

The simulation process follows five steps: (1) Setup, (2) Mission Definition, (3) Equipment Selection, (4) Unit Assignment, and (5) Results. A different page is dedicated to each step, and the workflow is shown across the top of the page for context. The mission and equipment together form the mission scenario.

Setup: Give the scenario a name and select a location from among from a list stored in the IPOWER database. Typical Model Year (TMY) data for each location is used to estimate the ambient temperature and solar irradiance at 30 min intervals throughout the simulated mission. [1]

Mission Definition: Select among standard activities stored in the IPOWER database to compose timelines that describe what the warfighters are doing and when they do it. Each timeline represents a "mission". Timelines can start on any date or time and have any length, but all the timelines in a simulation must start at the same time and end at the same time. Multiple timelines can be configured, saved, and reloaded. An example is shown in Fig 1.

Equipment Selection: Define the unit structure (e.g. a platoon consisting of four squads) and then assign equipment to individuals and to units. For example, a radio might be assigned to an individual warfighter, or a shared battery charger might be assigned to a squad. Equipment is assigned by creating a blank "system pane" and then choosing equipment from the IPOWER database to populate it. There are two ways to do this. Users can choose a load that always uses the same type of battery, in which case IPOWER will auto-populate the batteries. Alternatively, they can choose a power manager or hub that connects other equipment. In that case, IPOWER creates empty ports and users can choose among a list of compatible equipment to populate the ports. An example of the "System Builder" feature that enables systems to be created and visualized as block diagrams is shown in Fig. 2. At the top of the system
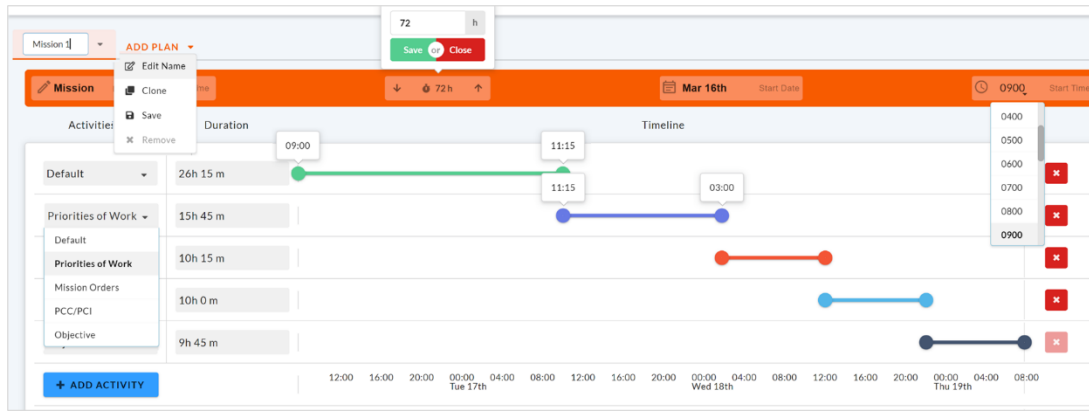
Figure 1. Mission definition step where users define one or more mission timelines using standard activities.

pane, users can define alternative configurations of the system and indicate which configuration is active during each mission activity. Multiple systems can be assigned to an individual warfighter or unit.
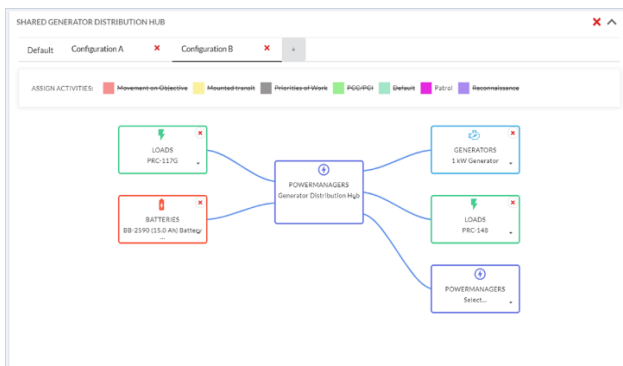

Figure 2. System pane with example system; in this case a power manager connected to a generator, two loads, a battery, and another power manager.

Unit Assignment: Choose which elements of the unit (e.g. squads) execute each mission from the Mission Definition step. IPOWER assumes units executing the same mission are co-located and able to share energy (batteries, fuel, etc.) and share equipment (battery charger, generator, etc.)

Results: Simulation results are communicated through metrics, plots, and charts. A summary is provided at the top of the results page and increasingly detailed results are available as users scroll down. Summary data includes the total amount of energy consumed, energy used to recharge batteries, number of batteries consumed by type, and weight of energy-related equipment needed for the simulated mission. Top-level plots include energy consumption, total energy stored in batteries, and energy harvested as functions of mission time.

There are constraints on the scenarios that can be configured in IPOWER; for example, systems that consume power but have no power source are not allowed. IPOWER checks for such problems during the configuration process, and when it finds one, it displays a descriptive warning with a link to the source of the problem so it can be rectified easily.

The steps in an IPOWER simulation are explained in the IPOWER Step-by-Step guide. [2]

Simulation Process

Fundamentally, IPOWER works by breaking the mission into many time steps, and then solving an energy balance for each system over each time step in sequence from the beginning of the mission to the end. For each time step, the process is:

1. Compute the power required by connected loads.
2. Compute power available from harvesters, generators, fuel cells, and batteries.
3. Balance power. Preferentially draw power from harvesters, generators and fuel cells, and batteries, in that order to satisfy the loads.
4. Update state variables, such as battery state of charge (SOC) and fuel consumed.
5. Advance to next time step

The process is shown in Fig. 3. IPOWER typically runs with a 3 min timestep and takes ~1 sec to complete a 72 h mission simulation for a platoon.
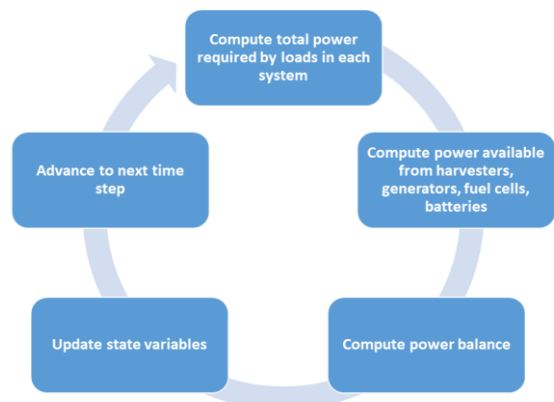

Figure 3. Basic simulation process in IPOWER.

Once a timestep is complete and the state variables have been updated, energy management features are applied for the next step. These energy management features play an important role in making IPOWER simulations realistic.

Battery management is a good example. If a battery is exhausted at the end of a timestep, IPOWER will look for a replacement in the "pool" of batteries carried by the unit. If one is available, then the batteries are swapped. If a battery charger is available, the mission activity allows the use of a battery charger, there is power for the battery charger, and a slot is available, then IPOWER will plug an exhausted battery into the battery charger.

When a battery is needed and none are available, IPOWER creates a new battery and adds it to the total that must have been carried from the beginning of the mission. This simple process yields the minimum number of batteries required to complete the mission. Preferentially drawing power from energy harvesters, generators/fuel cells, and then batteries yields the minimum fuel consumption constrained by the minimum number of batteries.

Structure and User Interface

As a web app, IPOWER consists of a front end that runs in a web browser and a back end that runs behind a server. The front end is predominantly JavaScript with TypeScript, and the back end is written in Go with a Postgres database. Each is containerized to make IPOWER modular and easily deployed. This structure was chosen both because of its flexibility and because it opened the way to a future service implementation.

The IPOWER user interface (UI) was designed in collaboration with a web development company and considered input from users to ensure it is simple and easy to use. Examples are shown in Fig. 4.
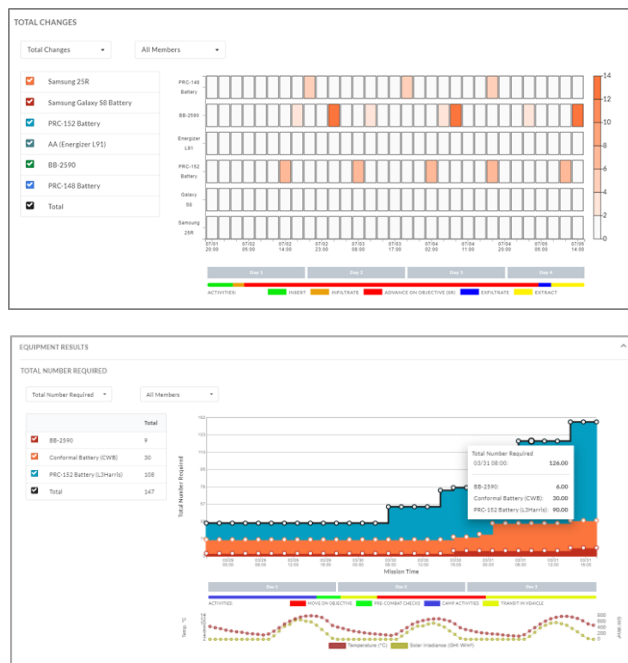

Figure 4. UI examples. A heat map showing when and how many batteries are replaced (top) and a plot of the number of batteries required as a function of mission time (bottom).

It was developed with standard web development tools, such as the React framework, to minimize the learning curve for new users and leverage the intuitive nature of many website features.

The IPOWER UI includes the ease-of-use features that would be expected for any application:

- Missions, equipment models, activities, and scenarios can be saved and later re-loaded.
- Mission timelines and units can be edited, cloned (copied), renamed, and deleted.

Plots on the results page include the mission timeline and estimated environment for context when interpreting the results. Hovering the cursor over plots and charts reveals pop-ups with detailed information. Many plots, including those shown in Fig. 4, include a legend where some curves can be turned off to focus on a specific result.

Equipment Models

IPOWER is delivered with several battery models based on battery characterization studies at NRL, however users are expected to provide the other equipment data relevant to their simulations. The user interface includes an "Admin" section where users can populate models for loads, batteries, energy harvesters, generators, fuel cells, and power managers. Each class of equipment has a series of pages that walk users through the configuration process, and once a model is created, any of the editable parameters can be updated. When a model is changed in the database, and the same model appears in a saved simulation, IPOWER will ask the user if the model parameters in the simulation should be updated to the values in the database.

All equipment models include metadata fields for a name, description, weight, and volume.

Load models can be defined in two ways:

- Define the power consumed during each mission activity.
- Define a set of operating modes and the power consumed in each mode. Define the duty cycle for each mode (fraction of time spent in that mode) for each mission activity.

Modifiers can be applied to change the power consumption of a load based on the ambient temperature or day/night. This feature can be used to configure equipment, such as night vision devices, for which the power consumption differs during day and night.

There are three types of battery model in IPOWER. The simplest is an "energy bucket" model that can be configured using basic information from a manufacturer's specification sheet. It is the least accurate, but simplest to configure. The dynamic battery model applies features of the battery discharge curve and chemistry to estimate more accurately the current and voltage for a given power flow. [3] The most detailed, the equivalent circuit model, uses an empirical equation of state to relate terminal voltage to SOC,

temperature, and power flow. The tables underlying the equivalent circuit model are populated at NRL by measuring battery series resistance and open circuit voltage as functions of SOC and temperature. [4] The equivalent circuit model responds to ambient temperature to capture effects such as reduced performance in cold environments.

All three battery models include fields for the minimum and maximum voltage, charging current, charging termination current, and maximum discharge current. These bounds influence the termination of the charge or discharge process, and they limit the power that can be withdrawn. They also influence the constant current/constant voltage charging profile typically used for lithium-ion batteries and simulated in IPOWER.

Solar panels are currently the only energy harvester in IPOWER. They are defined by an active area, efficiency, and temperature coefficient. IPOWER assumes they lay flat on the ground and uses the global horizontal irradiance to estimate the power production at each simulation time step.

Generator and fuel cell models are based on curves relating net power output to fuel consumption rate. The point at 0 W net output captures the idle fuel consumption rate. Parameters for startup energy cost and maximum idle time can be used to capture tradeoffs related to generator underutilization.

Power managers are the most complex equipment in IPOWER. They are defined by a fixed number of ports, the equipment compatible with each port, the directionality (in, out, or bidirectional) of each port, and the efficiency of each port. Power managers can be connected to other power managers to create complex system topologies. An iterative power balance within each time step is applied to systems with multiple power managers to ensure loads are satisfied efficiently.

Analysis Tools

IPOWER includes two tools for analyzing simulations. The comparison tool presents the results from two or more simulations side-by-side with corresponding results fields for easy comparison. The parametric analysis tool (PAT) can be used to vary one parameter in a simulation and then plot results over that range. For example, in a simulation with a battery, the battery capacity can be varied from a lower bound to an upper bound, and the number of batteries required for a mission will be plotted against that range. This tool is useful for understanding tradeoffs and identifying target values. For a goal, such as reducing battery weight by 10%, the PAT can be used to estimate how much radio efficiency and battery capacity would have to increase, and then use those results to pursue the least expensive solution.

Looking Forward

IPOWER is deployed as a standalone application that users run locally, however the IPOWER team is currently working to make it a cloud service. The new service-oriented approach has several benefits:

- It will be accessible from any internet connected computer via CAC login.
- Users can easily share equipment models, missions, and results.
- Organizations can maintain validated and verified models to ensure confidence in results.
- It can be updated and maintained efficiently, like most other software we use every day.

The ability to share and aggregate models and data will likely be the most valuable feature of the IPOWER service. Rather than starting from scratch, users will be able to build on the models and data accumulated by their organization. The service will run in the Air Force's Platform One DEVSECOPS environment. The IPOWER service is expected to become available in late 2023.

IPOWER includes a REST API between the front and back ends that will enable other DoD applications to interact with it if they are properly credentialed. The API is documented as an OpenAPI 3.0 specification. [5]

A new version of IPOWER is ready to be released as the first cloud service. Version 4.4 includes improvements to the user interface and a new feature, called Custom Power Management Logic, with which users can define custom state machines to govern how power managers behave.

Acknowledgements

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