Recommended Practice for Characterizing Devices' Ability to Provide Grid Services

Working Draft for Comment Only.
Do not Distribute.

RG Pratt
ZT Taylor

PNNL-26252

Recommended Practice for Characterizing Devices’ Ability to Provide Grid Services

Working Draft for Comment Only. Do not Distribute.

RG Pratt[1]
ZT Taylor[1]

---

[1] Pacific Northwest National Laboratory

Acronyms and Abbreviations

COP	coefficient of performance
DER	distributed energy resource
DOE	U.S. Department of Energy
FERC	Federal Energy Regulatory Commission
HVAC	heating, ventilation, and air conditioning
IEEE	Institute of Electrical and Electronics Engineers
NA	not applicable
NERC	North American Electric Reliability Corporation
PV	photovoltaic
SoC	state of charge
TES	thermal energy storage

Contents

Figures

Tables

1.0 Recommended Practice Purpose and Scope

Section 1.0 of this document is informative (not normative) and describes the overall intent, scope, and approach of the *Recommended Practice*.

1.1 Introduction

This document describes a *Recommended Practice* for characterizing the ability of various types of *devices* to provide a broad range of existing and emerging *grid services* and to characterize any potential impacts of doing so on other services that are their primary function. For the purpose of introducing this *Recommended Practice*, terms are defined as follows:

1. *Devices* – nontraditional power grid assets or equipment, commonly referred to as distributed energy resources (DERs), such as distributed storage and generation, end-use loads that offer some flexibility in their normal consumption patterns, and new and emerging grid-connected devices such as electric vehicles and hydrogen electrolyzers. The term *device* is used to refer to the hardware, i.e., equipment that consumes, stores, or produces power, and any controls and communications embedded in it, plus any separate controller that may be used to provide additional necessary functionality and digital communications to the grid. For example, unitary air conditioning equipment often requires an external controller (thermostat) for operation, and the thermostat is considered part of the *device*. The types of *devices* encompassed in the *Recommended Practice* are listed in Section 1.2.1.

2. *Grid services* – actions *devices* can perform that provide value to the grid and help it achieve a variety of required or desirable operational objectives. Typically, g*rid services* are defined as a set of performance requirements and a price or incentive mechanism that rewards *devices* based on their performance. *Grid services* may be defined solely to engage *devices* or, alternatively, to allow them to compete with traditional grid assets such as central power plants. The actions *devices* take to provide *grid services* are in the form of electric power they inject into the grid or adjustments in their level of consumption. The *grid services* encompassed in the *Recommended Practice* are listed in Section 1.2.2 along with the associated operational objectives.

3. *Net Load* – in general, *devices* provide services by changing their *net load*—defined as the power being consumed less that being injected into the grid by the *device*—that must be served by the grid's traditional assets: power plants, transmission lines, and distribution substations and feeders.

4. *Recommended Practice* – a procedure by which *devices* and their associated controls can be rated for their ability to provide individual *grid services*, and by which the individual ratings are combined into an overall rating or "Grid IQ." The ratings are designed to be suitable for use by device manufacturers (individually or as members of an organization), utilities and grid operators, DER aggregators, and other entities such as regions or states. The ratings are also designed to be suitable for informing consumers and others who may purchase *devices* based, in part, on their ability to perform *grid services* that are valued by utilities and grid operators. The *Recommended Practice* is embodied in the definitions and procedures described in Sections 2.0, 3.0, and 4.0.

1.2 Scope

The scope of the *Recommended Practice* in terms of the types of *devices* and *grid services* it encompasses is described here.

1.2.1 Device Classes Covered

The types of devices, i.e., *device classes*, covered in the *Recommended Practice* are the following:

- residential air conditioner or heat pump with smart thermostat
- residential electric water heaters (resistance and heat pump types)
- residential refrigerators
- commercial rooftop heating, ventilation, and air conditioning (HVAC) unit with smart thermostat
- chillers with building management system control
- commercial refrigeration systems with energy management system
- commercial building lighting with networked control system
- electrolyzers with hydrogen storage
- batteries with inverter
- electric vehicles with charger
- thermal energy storage (TES)
- photovoltaic (PV) solar arrays with inverter
- fuel cells with inverter.

The general functionality, performance requirements, and characterization and modeling procedures for each device are provided in Section 3.0.

1.2.2 Grid Services Considered

The *grid services* considered in this *Recommended Practice* and the associated operational objectives from which their value is derived are the following:

- **Peak capacity management** – Reduce *net load* as needed so that it never exceeds the capacity of the grid infrastructure to deliver power. Typically this occurs over a span of several hours on 10 to 15 of the hottest summer days of the year (or, for some regions, coldest winter days).
  - Objective – Reduce the need for capital expenditure for expansion and/or upgrades to generation, transmission, and distribution capacity.
- **Energy market price response** – Reduce *net load* when prices are high, with any associated increases in *net load* taking place when prices are low. This tends to occur in predictable, seasonal, daily patterns over periods of a few hours when power plants with expensive fuel and/or low efficiency are required to supply power. Random disruptions to

daily patterns may be due to weather conditions, plant outages, shortages in output from renewable generation, or unusual wholesale market conditions.

  - Objective – Reduce wholesale energy production and/or purchase costs.

- **Meet obligation to supply capacity in a wholesale energy market –** Reduce net load when called upon by an independent (transmission) system operator to meet a contractual obligation to do so, for which they have received a capacity payment (often through a market intermediary known as an aggregator). When provided by DERs, this *grid service* is typically utilized as reserve capacity for extreme events lasting a few hours, and may be called upon at any time as a performance test.
  - Objective – Ensure sufficient regional generation capacity exists and obtain it from the lowest-cost resources using a wholesale capacity market.
- **Frequency regulation –** Increase or decrease net load to restore balance between supply and demand in response to a ~4-second-interval signal from the grid operator. This service is traditionally supplied by power plants, which take many seconds up to a few minutes to respond.
  - Objective – (fast regulation) Maintain grid frequency within acceptable range in the face of continual, momentary imbalances between supply and demand; imbalances vary from oversupply to undersupply within ~1 minute or less.

    – (slow regulation) Maintain contractual balance of imports and exports for a regional balancing authority's balancing area; imbalance varies from oversupply to undersupply within 10–15 minutes (slow regulation may or may not be combined with fast regulation into a single service).
- **Spinning reserve –** Remain on standby, ready and able to rapidly reduce net load and sustain the reduction until it is replaced by generators that are available but off line (typically 15–30 minutes).
  - Objective – Rapidly restore balance between supply and demand when a large grid asset (power plant or transmission line) suddenly and unexpectedly trips off line. Spinning reserve is required to prevent blackouts.
- **Ramping –** Remain on standby, ready and able to rapidly increase or decrease net load when the available generation cannot change its output rapidly enough to follow changes in total net demand (regional load less total renewable output). This is a new type of service, whose need is being driven by rapid penetration of renewables. It is typically used in either of two situations. In regions with high levels of solar generation, the service is engaged over a couple of hours in the morning and late afternoon when insolation levels are in rapid transition. In regions with large amounts of wind power, it is called upon if the timing of a forecasted change in the wind speed is off by an hour or two.
  - Objective – Meet the requirement to rapidly change the output of total generation to maintain balance between supply and demand in response to rapid changes in power production by renewables.
- **Artificial inertia –** Remain on standby, ready and able to detect when grid frequency drops rapidly, and act to complement the grid's angular momentum and generator governor controls by instantly and autonomously decreasing net load (within ~1 second; less is preferred). Inertia is traditionally supplied by a combination of the angular momentum of turbines in steam- or hydro-based power plants and autonomous governor controls on large

generators; there is emerging need to supplement these sources with a new type of service as renewable generation displaces steam-based plants.

  - Objective – Slow and stop the otherwise precipitous change in frequency that begins instantly when a large grid asset (power plant or transmission line) or a similar amount of load suddenly and unexpectedly trips off line and creates a large imbalance between supply and demand.

- **Distribution voltage management** – Remain on standby, ready and able to detect when the distribution voltage drops rapidly, and act instantly and autonomously by rapidly adjusting net load in the form of its reactive and/or real power components (within ~1 second; less is preferred). This is a new type of service, the need for which is driven by rapid penetration of distribution-connected solar generation. Rapid changes in the combined power output from such systems can occur due to crossings of cloud fronts, which can result in unacceptable voltage fluctuations.

  - Objective – (fast response) Maintain distribution system voltage within the normal range in response to rapid changes in net demand for power.

    – (slow response) Assist in maintenance of distribution system voltage within the normal range by coordinating reactive power output with distribution-voltage management systems (transformer tap changers, voltage regulators and capacitor banks), either on command or autonomously, based on self-sensed voltage fluctuations.

The performance requirements, device usage patterns, and performance metrics for each *grid service* are provided in Section 4.0.

1.2.3 Eligibility Requirements for Providing Grid Services

The term *eligibility* in the context of this *Recommended Practice* is used in two ways:

1. For a *device* to be *eligible* to provide *grid services* in general, and hence for it to be relevant to undergo the characterization and rating procedures of the *Recommended Practice*, it must be capable of changing its load or power injection, in response to signals sent by the power grid and/or autonomously in response to self-sensed frequency or voltage. Some *grid services* explicitly or implicitly require *devices* to be capable of two-way communications.
2. *Eligibility* to provide a given *grid service* in practice is formally determined by the grid operator that has defined the service, its performance requirements, and the rules under which *devices* are allowed to participate in it. Thus, *eligibility* to supply a *grid service* in practice and receive payments or incentives for doing so is ultimately decided by regional jurisdictions acting within the supervision of the Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC).

1.3 Purpose

The intent of the *Recommended Practice* is described in this section.

1.3.1 Inform Utilities and Grid Operators about Device Capabilities

The purpose of the power grid is to generate and deliver reliable, affordable, and clean electricity to consumers where and when they want it. One of the primary challenges facing the

U.S. power grid is that generation is rapidly shifting from centralized to more distributed forms, and from being entirely fuel-based and highly dispatchable to including renewable-based forms that are significantly intermittent and stochastic in nature. Operating such a grid to meet society's demands for reliability and affordability will require new forms and vastly increased amounts of operational flexibility. This flexibility is largely embodied in *grid services* that today are provided by power plants but are increasingly reflected in wholesale market products or utility programs in which *devices* participate. To meet the requirements for flexibility at reasonable cost, much of it is expected to be derived from services provided by large fleets of *devices* in the future.

In order for there to be an informed and expanding marketplace for *devices*, grid planners and operators need to be able to accurately and conveniently assess and value their capabilities to provide *grid services* and to have confidence they will perform as expected in the field. As the number of *devices* deployed grows and their capabilities are improved and expanded over time, it is critical to understand the potential resource they represent. By providing proven, standard performance characteristics along with models for their ability to provide *grid services*, utilities and grid operators can design markets or other operating strategies and make decisions on *device* purchases, subsidies, and rebate programs. Further, incorporating these characteristics and models into the tools used to plan and operate the grid will help utilities and grid operators accurately assess the contribution *devices* offer at both the planning and operational time scales. As a result, general electricity ratepayers can receive cleaner, more reliable electricity at lower cost than will otherwise be possible without the participation of *devices*.

1.3.2 Inform Consumers about Device Capabilities

Consumers and third-party device owners may receive direct incentives, payments, or credits on their energy bills in compensation for their *device's* contribution to grid operations. Such incentives are expected to be increasingly available over time, particularly as the ability of *devices* to provide a growing number of valuable *grid services* becomes broadly recognized. This *Recommended Practice* is intended to provide independently validated metrics of *device* performance with which purchasers can make informed decisions.

1.3.3 Accelerate Market Adoption

This *Recommended Practice* is intended to help manufacturers by accelerating the market adoption of *devices*, systems, and associated controls capable of providing *grid services*. It is designed to help them sell more equipment by enabling an informed marketplace. Device purchasers (i.e., utilities, third parties, and consumers) must be confident that their investments can be recouped through the prices or incentives offered by the grid for services rendered. This will allow the marketplace to reward manufacturers via increased sales of *devices* with advanced capabilities, based on the quality and value of their performance.

1.3.4 Encourage Innovation by Device Manufacturers

This *Recommended Practice* is intended to encourage *device*, system, and control manufacturers to add the capabilities needed for *devices* to supply existing and new *grid services* by helping them understand the wide variety and nature of the opportunities they present for their products. It can recognize and reward such innovation by clearly articulating the responses required and by providing standard metrics for performing *grid services* and the value obtainable. This enables manufacturers to target the best opportunities for their *devices*, and avoid those where the marginal cost of added capability is not worthwhile to their customers. Manufacturers who innovate can then advertise the new and improved features of their *devices'* models in the context of their potential value to market stakeholders.

1.3.5 Identify Services that are Inappropriate for a Device

An important purpose of this *Recommended Practice* is steer manufacturers and utilities or grid operators away from certain opportunities for *devices* to provide a *grid service* when undesirable side effects of doing so outweigh the benefits to *device* owners and users. These effects may include such things as increased energy consumption compared to baseline usage patterns, unacceptable effects on user comfort or other amenities a device provides, reduced equipment lifetime due to increased wear and tear, or even equipment damage and warranty violations.

1.3.6 Encourage Manufacturers to Build Self-Protection into Device Controls

By clearly articulating the nature of the response required to provide *grid services*, the *Recommended Practice* helps manufacturers understand how to add protective controls to their *devices* so that the *devices* cannot, under any circumstances, engage in actions that will damage them or reduce their lifetime unacceptably. An example of such protective controls are restrictions on rapid cycling of equipment that must warm up or cool down before changing its operating mode from “on” to “off” or vice versa (e.g., equipment that uses refrigerant cycles).

1.4 Functional Objectives

The functional objectives for the *Recommended Practice* shape the general framework and technical approach it uses to characterize *devices* and rate their ability to provide *grid services*. These objectives are described in the following subsections.

1.4.1 Test Protocol Simplicity

The federal government, including the U.S Department of Energy (DOE), does not have a statutory mandate to test *devices* and rate their ability to perform *grid services*. Therefore, it is critical that the test procedures in the *Recommended Practice* be short and simple enough that they do not place an undue burden on manufacturers and/or organizations who may adopt or choose to use it voluntarily. The goals are to

- Leverage existing industry-standard and/or statutorily required test protocols and results as much as possible; for example, from tests for appliance efficiency or inverters.
- Where extensions to existing testing protocols are required, build on the apparatus and procedures used in the existing protocols to the extent practicable.
- Keep the test time of any extensions to physical testing protocols as short as possible, preferably to less than 24 hours.

1.4.2 Rating Device Performance as a Fleet Member

Many *grid services* require changes in power injection or net load to follow a dispatch signal from the utility operator and respond in proportion to its magnitude. Taken at face value, this requirement would exclude participation of *devices* like air conditioners or water heaters that cannot provide continuously variable changes in energy generation or consumption and that may not be capable of rapid switching between “on” and “off” states. Further, market-based *grid services* often require participants to offer a quantity or capacity roughly the size of a small combined-cycle turbine power plant (~50 MW).

To allow *devices* limited by these requirements to participate in providing *grid services*, these *devices* may be aggregated through a coordinated control mechanism that enables them to act in combination to provide the required quantity and a proportional response. Just as the most complex analog signals can be effectively composed by superimposing small, discrete digital signals, smooth proportional signal-following responses can be composed from the discrete on/off responses from many small devices. Hence, the *Recommended Practice* must rate a *device’s* ability to provide a *grid service* as a member of a large fleet*,* so that it appropriately recognizes the potential of small and discrete *devices*.

When multiple instances of a *device* are needed to provide a *grid service* with the required fidelity, metrics for their performance will be derated accordingly.

1.4.3 Uniformity across Device Classes and Grid Services

It is important that the *Recommended Practice’s* performance metrics be defined in a way so that they are uniform and consistent across *device classes* and *grid services*. From the perspective of utilities and grid operators, this allows the performance of various types of *devices* to be compared and contrasted in a meaningful way. Doing so also allows the value of providing various *grid services* to be compared similarly. Further, it is desirable for the performance metrics to be normalized to the size (capacity) of the *device* so that the performance of *devices* of different sizes can be meaningfully compared.

1.4.4 Ratings for Future Services or for a Region

Grid services are continuously being defined or redefined as the operational objectives of the power grid grow more complex. Details of these definitions also vary by region and by jurisdiction. In addition, the relative need for various services also varies depending upon regional weather, load characteristics, and mix of generation (especially its renewable content). Thus, performance metrics for *grid services* depend, in part, on standard assumptions about these varying factors. Therefore, the *Recommended Practice* must be designed so that these key assumptions can be readily changed to produce metrics for a specific region or a newly defined or modified *grid service*. Further, the *device* characteristics assessed during *device* testing must be sufficiently general that metrics for the performance of new *grid services* developed at some future date can be computed without requiring that *devices* be retested.

1.5 Approach Summary

In order to serve the intent and meet the functional objectives described in Sections 1.3 and 1.4, respectively, the *Recommended Practice* comprises components with key properties as described in the following subsections.

An illustration of the components and processes is shown in Figure 1.1. The primary components of the *Recommended Practice* are indicated by the blue rectangles. External processes or information are indicated by the orange ovals. The primary information flows through the *Recommended Practice* are shown as yellow block arrows.

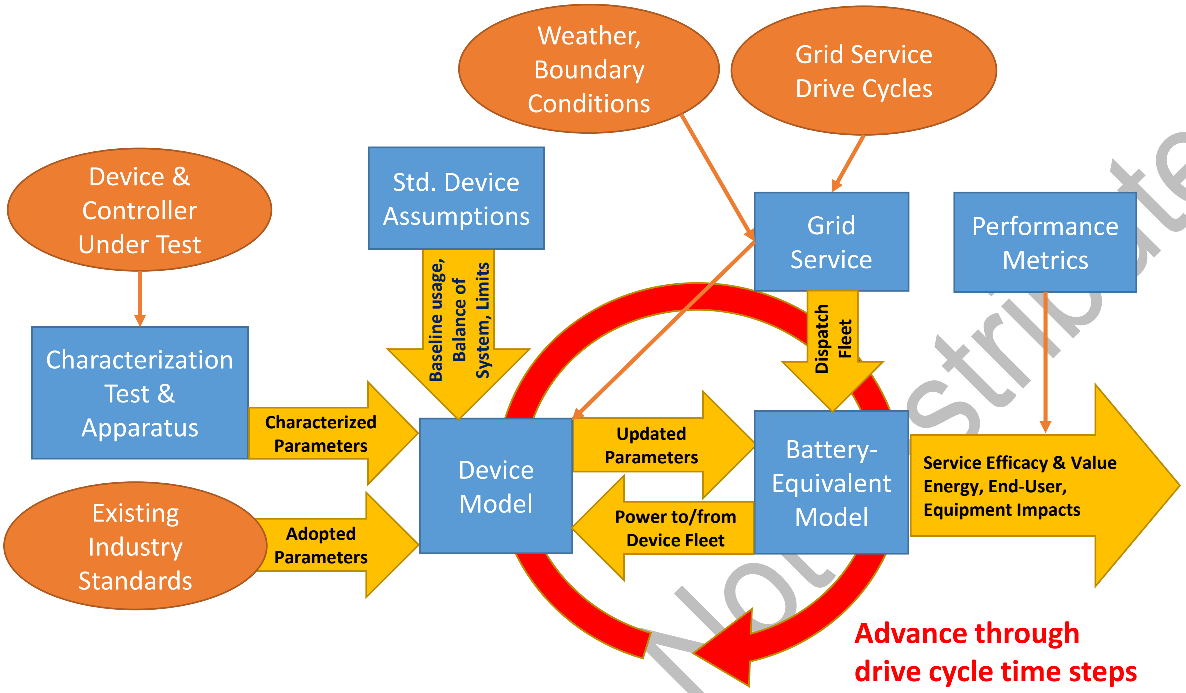

Figure 1.1. Primary Components of the *Recommended Practice*

1.6 Characterization Test

The *characterization test* is a procedure for measuring all the physical and control parameters of a *device* and its controller(s) that are needed to define its performance of <u>any</u> foreseeable *grid service*. It focuses exclusively on the measurement of key parameters and does not involve time-series testing against actual, individual *grid services*, since doing so would take too long and would limit the ability to develop ratings for *grid services* other than those specifically tested. The *Recommended Practice* may adopt parameters from existing test procedures that define a *device's* power input and output capacities and rate of change, energy input and output conversion efficiencies, and energy storage capacity in various operational modes and conditions. To the extent these adopted parameters are insufficient for the purposes of this *Recommended Practice*, the characterization test will define a test apparatus and sequence of tests to measure the parameters.

In addition to these power- and energy-related parameters, *grid services* are generally also defined by the potential duration of *device* response and transition times or limits on changes from one operational state or mode to another. So, unlike most existing *device* testing procedures, measuring parameters that describe these limits is a key focus of the *characterization tests*. The transition times or limits may be a function of a device's inherent physical properties or of its control system(s). The *characterization tests* are designed to separately distinguish their source and their effects. The *characterization tests* are <u>not</u> designed to measure communication network time lags between the utility operator and the *device* controller, since these vary with the network design and traffic levels. They are also <u>not</u> designed to test the communication protocols used by the manufacturers for their compatibility or interoperability with communication standards. Such testing is the subject of other DOE activities.

1.6.1 Device Model

The physical and control parameters measured for a device by the characterization test procedure(s) are used to construct an engineering-based model of the device being characterized. The *device model* must also include the timing parameters measured by the *characterization test*. The *device model* is completely independent and unaware of the specifics of any *grid service*. It is simply used to obtain a current set of parameters that describe a *device* fleet's status and capabilities at any given time, either under baseline conditions or while providing a grid service, given its current boundary conditions and time history.

Device models are necessarily specific to each device class (or subclass), because of differences in the *devices*' physical design and function. The *device model* must reflect the power- and energy-related parameters of the *device* as a function of the operational conditions imposed on it by its normal usage pattern and when supplying *grid services*. In some cases, this includes a standard definition for the balance of the physical system involved, which may not have been subject to the *characterization test*. An example is the thermal properties of a building served by an air conditioner or a TES system. An entity adopting this *Recommended Practice* can change the standard assumptions about the balance of system for a *device* class to better represent the population of *devices* in a region, for example.

In addition, the *device model* may include standard assumptions about any normal, baseline usage pattern(s) for the *device*, and limitations or requirements placed on it by its owners or users when it serves purposes other than providing *grid services*. Electric vehicles, for example, have a baseline charging pattern and owner operational requirements (such as their readiness for travel at a given time) that restrict their availability to provide *grid services* and must be taken into account by the *device model*. A second example is an air conditioner whose operation is constrained by limits on the extent and duration of indoor air temperature deviations from normal thermostat set points imposed by the occupants.

1.6.2 Representative Service Drive Cycle

For the purposes of this *Recommended Practice*, a *grid service* is represented as a *drive cycle* consisting of a required time-series definition of the power injected (or consumed), its price or per-unit value, and any associated boundary conditions needed by any *device model* such as weather conditions. Because the availability of devices varies diurnally and seasonally, the *drive cycle* must represent the entire year, but for practical reasons does not necessarily contain data for each time interval in a year, particularly if a grid service operates on a very short time scale (e.g., frequency regulation, voltage regulation, or artificial inertia). In such cases, representative days or seasonally representative events may be used to lessen unwarranted computational burden when calculating performance metrics.

The data comprising the *drive cycle* is chosen to represent conditions typical for the United States in 2016. It may be actual data obtained from a market, or from a model of grid operations. It is necessarily specific to a region and to the characteristics of its power grid and/or markets. New or modified *grid services*, as well as associated conditions such as weather representative of a specific region, may be defined by an entity adopting this *Recommended Practice* as needed.

1.6.3 Battery-Equivalent Model

For the *Recommended Practice's* performance metrics for a *grid service* to be comparable across various classes of *devices*, each *device* class must be dispatched by a *grid service* in a common fashion, rather than with a *device*-specific coordination algorithm. This is also valuable for practical reasons, since a large number of such algorithms would have to be developed if they were specific to each combination of *device* class and *grid service*, and it would be nearly impossible to assure that they offered equivalent opportunity to each class.

Therefore, each *device model* in the *Recommended Practice* translates its power, energy, and timing parameters into the form of a *battery-equivalent model* so that, from the perspective of a *grid service*, only a single, relatively simple coordination scheme is used to "dispatch" a *device* of any type. The term "battery-equivalent" is used to imply that the normal properties of a battery may be supplemented by additional parameters required to describe *devices* generally for the purposes of the *Recommended Practice*. Regardless, as the *grid service* marches through time in order to compute the performance metrics, it simply attempts to "dispatch" an equivalent battery fleet to provide the entire service while staying within the physical and user-based limitations of the fleet as updated by the *device model* at each time step. Thus, it is agnostic about what method among many possibilities would be used by avoiding specification of details regarding how *devices* would actually be coordinated in practice, and yet it remains true to the limitations on the response of individual devices.

1.6.4 Scaling a Device Fleet to the Drive Cycle's Magnitude

A *device* fleet's ability to perform a *grid service* is directly tied to its size relative to the magnitude of the service. Such a fleet, incapable of providing the service as individuals because they cannot respond to a proportional dispatch signal with enough fidelity, quantity, or duration, may be able to provide the service very nearly perfectly if it is overly large for the task. Since it is the intent of this *Recommend Practice* to draw out distinctions such as this between the availability and technical capability of *devices* to perform a given *grid service*, it is important to meaningfully scale the fleet of devices to the magnitude of the service. This scaling is performed by matching the nameplate (nominal) power input and/or output capacity of the *device* fleet to the maximum power input or output in the *grid service drive cycle*. In Figure 1.1, the scaling process is conducted inside the "Device Model" block.

1.6.5 Performance and Impact Metrics

This *Recommended Practice* defines a range of performance metrics that describe how well a *device* can provide each *grid service* and the coincident impacts on the *device's* energy consumption, on the owner or user, and on the *device* itself. This subsection provides an overview of these performance metrics.

It should be noted that in this *Recommended Practice,* the ratings for a *device's* ability to perform a *grid service* and other impacts are based on the *drive cycles* defined for each *grid service*. They only provide meaningfully representative information for comparing one *device's* performance relative to another, rather than representing a blended average for the United States or localized values for each region.

1.6.5.1 Grid Service Performance Metrics

Grid service performance metrics are the primary metrics of device performance that result from application of the *Recommended Practice*. Three fundamental metrics or ratings will be computed for each *grid service*:

- **Service Efficacy** – the fraction of the *grid service drive cycle's* total energy that the *device* fleet was able to supply
- **Value Efficacy** – the fraction of the *grid service drive cycle's* total value that the *device* fleet was able to supply
- **Value Provided** – the total annual value ($/yr) the *device* fleet was able to supply for the *grid service*.

The first two metrics provide useful measures normalized by the scale of the *device*, and hence relate the *quality* of a device's ability to respond, while the third provides an absolute metric for the value obtainable. That can be related to the *device's* absolute cost or marginal cost. In addition, the *Recommended Practice* provides overall metrics for service efficacy, value efficacy, and value produced based on the sum total energy and value across all the *grid services*. These metrics are formally defined in Section 2.6.1.

1.6.6 Energy Impact Metrics

It is important that the provision of *grid services* does not adversely affect consumers' energy bills or national or regional goals for energy efficiency. So the *Recommended Practice* provides three metrics for the impact of providing each *grid service* on the energy consumption of a *device*:

- the ratio (in percent) of the *device's* annual energy consumption while providing a *grid service* to the *device's* annual energy consumption when not providing the *grid service*
- the change (kWh) in energy consumption associated with providing a *grid service*
- the cost of the change in energy consumption associated with providing a *grid service*.

In addition, the *Recommended Practice* provides an overall energy cost metric that is the simple sum of the cost metric across all of the *grid services*. These metrics are formally defined in Section 2.6.2.

1.7 End-User Impact Metrics

The *Recommended Practice* provides end-user impact metrics pertinent and specific to each *device* class. Defined as part of the *device model* for each class, these include impacts on normal consumer amenities that are expected from the *device* class (aside from any value obtained in exchange for the performance of *grid services*). These are defined in Section 3.0 for each *device* class when relevant. An example is the number of degrees and duration of higher-than-normal indoor air temperatures that may occur when an air conditioner is responding to provide a *grid service*.

1.8 Equipment Impact Metrics

It is beyond the scope of this *Recommended Practice* to provide estimates of the effect of providing a *grid service* on the lifetime of a *device*. Such an analysis is *device*-specific and best left to the manufacturer with a vested interest in both consumer satisfaction and value. The *Recommended Practice* does provide metrics or indices of potential impacts on *devices* from which manufacturers can make their own independent estimates. These are defined in Section 3.0 for each *device* class when relevant. Examples include

- any change in the number of cycles per year as a result of providing a *grid service*
- any change in the depth of cycles per year as a result of providing a *grid service*.

2.0 General Definitions

This section provides normative definitions of terms generally applicable to all types of *devices* and *grid services* within the scope of the *Recommended Practice*. (See Sections 2.1.1 and 2.5.1 for definitions of these terms.)

The definitions in this section shall apply unless modified or otherwise specified for specific subsections of Sections 3.0 or 4.0 of the *Recommended Practice*.

All definitions shall apply whether used in singular or plural form (nouns) or in various tenses (verbs).

Formally defined terms when used in the text of the *Recommended Practice* will always appear in italics.

2.1 Definitions Related to Devices

2.1.1 Device

Device **–** For the purposes of this *Recommended Practice,* the term *device* refers to a system comprising one or more of the following components:

1. hardware (i.e., equipment that consumes, stores, converts, or produces power)
2. any controls and communications embedded in the hardware
3. a separate controller that may be used to provide additional functionality and digital communications for the hardware and any embedded controls and communications.

2.1.2 Device Class

Device Class **–** For the purposes of this *Recommended Practice,* the term *device class* refers to the family of similar *devices* that share

1. a common engineering model and boundary conditions
2. common changes in their operation when responding to provide grid services, in terms of its consumption or output of real or reactive power (in qualitative rather than quantitative terms)
3. standard assumptions about any normal, baseline usage pattern(s) for the *device*, if the *device's* primary purpose is not the provision of grid services
4. standard assumptions about limitations or requirements placed on the *device's* use by its owners or users when used to provide grid services.

2.1.3 Device Under Test

Device Under Test – For the purposes of this *Recommended Practice,* the term *device under test* refers to a *device* subjected to or submitted by a manufacturer for characterization testing and ratings (metrics) of its ability to provide *grid services* and any associated impacts thereof. The *device under test* should be defined and provided by the manufacturer in one of the following forms (or combination as appropriate):

1. *Equipment* – the hardware comprising the *device under test* defined in this *Recommended Practice*, including any controls and communications embedded in it
2. *Separate Controller* – a controller supplied separately from the *equipment* as part of the *device under test* that may provide digital communications to the grid as well as interpret the *device's* state and availability, that is supplied separately from the *device* and that is an element of a *device class* defined in this *Recommended Practice*
3. *System – a system* comprising both the equipment and a suitable separate controller, both of which are elements of a *device class* defined in this *Recommended Practice*.

If the *device under test* consists solely of a piece of equipment, only the parts of the *Recommended Practice* applicable to hardware of the relevant *device class* apply (with a prototypical controller simulated as part of the balance-of-plant assumptions).

If the *device under test* consists solely of a controller, only the parts of the *Recommended Practice* applicable to the controller apply (with a prototypical equipment element simulated as part of the balance-of-plant assumptions).

2.1.4 Modes

Modes – For the purposes of this *Recommended Practice*, the term *modes* refers to various states of operation a *device* goes through as it achieves its primary objective(s) in normal operation. These modes are specific to each *device class* as defined in Section 2.2.1. *Modes* may be mutually exclusive ("on" vs. "off," "charging" vs. "holding" vs. "discharging"), or additive, i.e., modifying another mode (e.g., for an air conditioner "on" and "heating," "cooling," or "inactive"). The description of *modes* for the *device under test* should include any restrictions imposed by the manufacturer on the types, and circumstances (e.g., timing or triggering), of allowed transitions from one *mode* to another.

2.1.5 Relevant Modes

Relevant Modes – For the purposes of this *Recommended Practice*, the term *relevant modes* refers to *modes* that the manufacturer deems meet at least one of the following criteria:

1. They affect more than 5% of typical annual energy consumption or output for the *device under test* under typical or average usage conditions.
2. The *device under test* operates in the *mode* more than 5% of the year under typical or average usage conditions.
3. They affect power consumption or output by more than 5% compared to other *modes* for the *device under test* under typical or average usage conditions.

4. The mode is an essential state in the operation of the *device* that has impacts on the provision of *grid services* (even if said state does not directly significantly contribute to any given *grid service*).
5. The *mode* is solely for the purpose of providing *grid services*.

The manufacturer subjecting or submitting a *device under test* should declare all *relevant modes*, as they will be needed for the *characterization tests* and *device models* of this *Recommended Practice* (see definitions for these terms in Sections 2.2.1 and 2.3, respectively). To encourage innovation on the part of manufacturers, any details of a *device under test's relevant modes* need not be revealed, only their existence.

2.1.6 Grid Service Responses

Grid Response Responses **–** For the purposes of the *Recommended Practice*, the term *grid service responses* refers to the way(s) in which a *device* adjusts its energy consumption or generation to provide *grid services*.

The manufacturer subjecting or submitting a *device under test* should declare it capable of at least one of the following *grid service responses* when operating in at least one *relevant operating mode*:

1. ***Adjust Real Power*** **–** For the purposes of the *Recommended Practice*, the term *adjust real power* refers to increasing or decreasing a *device's* consumption or output of real power (e.g., in units of kW).
2. ***Adjust Reactive Power*** **–** For the purposes of the *Recommended Practice*, the term *adjust reactive power* refers to increasing or decreasing a *device's* consumption or output of reactive power (e.g., in units of kvar).

Adjusting the real power output or consumption in some *devices* may cause a corresponding change in reactive power output or consumption that is dependent rather than being independently adjustable. In such cases, the *device's* declared *grid service response* shall be the one that is intended.

It is possible for a *device* to be capable of adjusting real power and reactive power independently, in which case both capabilities should be declared. Note that it is also possible for both capabilities in such a *device* to each have dependent effects attributed to them).

The *characterization tests* of the *Recommended Practice* are designed to reveal these relationships.

The manufacturer subjecting or submitting a *device under test* should declare all relevant *grid service responses* of which the device is capable.

2.1.7 Means of Response

Grid service responses can be implemented in any way deemed appropriate by the manufacturer of the *device under test*. For the purposes of the *Recommended Practice*, the *means of response* for a *device* is the means by which a *device* implements *grid service responses*, which are classified as one or more of the following:

1. ***Mode Change*** – changing a *device’s* operating mode
2. ***Control Setting Change*** – changing a *device’s* control setting such as a set point, an operating range, a deadband, a proportional control setting, etc.
3. ***Modulation*** – modulating a *device’s* energy consumption or generation across a continuous range.

2.1.8 Discrete and Continuously Variable Responses

For the purposes of the *Recommended Practice*, *grid service responses* are further classified as being of the following types:

1. ***Discrete*** – The *device* adjusts its real and/or reactive power consumption or generation in discrete levels, often by changing its operation from one mode to another. This is common to many types of loads, for example, that may switch from “on” to “off” or from “active” to “inactive.” Multistage *devices* may have more than one discrete level of real or reactive power consumption or output.
2. ***Continuously Variable*** – The *device* adjusts or modulates its power consumption or generation across a continuous range.

The manufacturer subjecting or submitting a *device under test* should identify each *grid service response* of which the *device* is capable as either *discrete* or *continuously variable*.

2.1.9 Signal-Based and Autonomous Responses

For the purposes of the *Recommended Practice, grid service responses* are further classified as one or more of the following types:

1. ***Signal-based*** – The *means of response* is activated by a communicated signal external to the *device under test.*
2. ***Autonomous*** – The *means of response* is activated by the *device under test* based on self-sensed grid conditions (e.g., frequency or voltage at the point of common coupling).

The manufacturer subjecting or submitting a *device under test* should identify each *grid service response* of which the *device* is capable as either *signal-based* or *autonomous*.

2.1.10 Specification of Communications

Communications – For the purposes of the *Recommended Practice*, the term *communications-based response* refers to the ability of a *device* to alter its operating state in response to a communication signal received from an external grid operator or third-party delegate thereof (such as an aggregator of multiple *devices*).

While testing the communications protocols used by the *device under test* for their interoperability with existing standards is outside the scope of this *Recommended Practice*, for purposes of conducting the characterization tests the manufacturer subjecting or submitting a *device under test* should declare the following:

1. ***Communications Medium*** – the medium (e.g., WiFi, Ethernet, etc., used for communications to the *device under test*

2. ***Communication Protocol*** **–** the communication protocol to be used for communications from the *test apparatus* (see Section 2.2.5) to the *device under test* (e.g., from among standards available in the *test apparatus*; potential examples include TC/IP, BACnet, SEP2, OpenADR, Modbus, etc.)

3. ***Syntax for Commands*** **–** the syntax for the commands used to

    a. evoke each grid service response from the *device under test* that is signal-based

    b. modify the parameters controlling and enabling/disabling each *autonomous response* from the *device under test* (see Annexure 5.0).

If either the *communications medium* or *communications protocol* used by the *device under test* is not supported by the *test apparatus* for a *device class*, the manufacturer should supply a communications system capable of scheduling and issuing the relevant commands so that the *characterization test* specified by this *Recommended Practice* can be conducted.

2.2 Definitions Related to Characterization Test

2.2.1 Characterization Test

Characterization Test **–** For the purposes of this *Recommended Practice*, the term *characterization test* refers to the series of tests defined to characterize a *device's* ability to perform *grid services*, in general. *Characterization tests* are generally specific to each *device class* as defined in Section 3.0, with the exception of *autonomous grid service responses* (i.e., responses to self-sensed frequency or voltage) for which *characterization tests* common to all devices are defined in Annexure 5.0.

The *characterization test* for a *device class* in this *Recommended Practice* may build upon existing or proposed standardized tests, such as for DOE appliance and equipment efficiency standards or interconnection standards for inverter-based distributed generation and storage (IEEE 1547),[2] as defined in Section 3.0.

2.2.2 Characterized Parameters

Characterized Parameters **–** For the purposes of this *Recommended Practice*, the term *characterized parameters* refers to key parameters, measured by the *characterization test* for the *device class*, that define and bound the responsiveness of the *device under test* and that are required to model a *device's* ability to provide any *grid service*. For example, the *characterized parameters* generally include, for each of its *relevant modes* (*m*),

1. ***Change in power*** **–** the amount of change in the *device under test's* real and reactive power consumption or output when each *grid service response* is invoked (ΔP_m and ΔQ_m, where an increase in output or a decrease in load is defined as positive, in kW and kvar for real and reactive power, respectively)

---

[2] IEEE 1547-2003, *Standard for Interconnecting Distributed Resources with Electric Power Systems*. Institute of Electrical and Electronics Engineers, Piscataway, NJ. Available at https://standards.ieee.org/findstds/standard/1547-2003.html.

2. ***Equipment time lag*** **–** the time lag between when the equipment (i.e., hardware) of the *device under test,* including any controls and communications embedded in it, receives the invoked command for a *grid service response* and when it begins to change its real and reactive power consumption or output (Δt_equip_m, in seconds)
3. ***Separate controller time lag*** – the time lag between when any separate controller for the *device under test* receives the invoked command for a *grid service response* and when the equipment's embedded controls receive the command ($\Delta t\_controller_m$, in seconds, defined as zero if no separate controller is present)
4. ***Time to full response*** **–** the time lag between when the *device under test* begins to change its real and reactive power consumption or output and when it reaches its maximum response ($\Delta t\_full\_response_m$, in seconds)
5. ***Ramp rate*** – the rate of change of the *device under test's* real and reactive power consumption or output (dP_m/dt and/or dQ_m/dt, defined as ΔP_m and/or ΔQ_m divided by $\Delta t\_full\_response_m$, in units of kW/sec or kvar/sec, respectively)
6. ***Response duration*** **–** the duration of the *device under test's grid response*, defined as the time between when it reaches its maximum response and when it terminates the response, or the maximum duration of response defined by other assumed or adopted parameters defined for the *device class's characterization test*, as defined in Section 3.0
7. ***Energy storage capacity*** **–** the amount of energy that can be stored by the *device under test*
8. ***Charging efficiency*** **–** the efficiency of the *device under test's* conversion of energy from standard alternating current (AC) power to the device's storage (which for some *device classes* may be part of an assumed *balance of system*)
9. ***Discharging efficiency*** **–** the efficiency of the *device under test's* conversion of energy from the *device's* storage to standard AC power (which for some *device classes* may be part an assumed *balance of system*).

Additional *characterized parameters* may be measured by the *device class's characterization test* as defined in Section 3.0.

2.2.3 Adopted Parameters

Adopted parameter – For the purposes of this *Recommended Practice*, the term *adopted parameter* refers to a parameter measured or calculated based on results from existing or proposed standardized tests incorporated by reference in this *Recommended Practice*, such as for DOE appliance and equipment efficiency standards or interconnection standards for inverter-based distributed generation and storage (IEEE 1547), as defined for a given *device class* in Section 3.0.

2.2.4 Assumed Parameters

Assumed parameters – For the purposes of this *Recommended Practice*, the term *assumed parameter* refers to a parameter whose value is a standard assumption of the *Recommended Practice*, as defined for a given *device class* in Section 3.0.

These are often associated with the need to assume information about the *balance of system* (see Section 2.2.6) associated with a *device class* in order to determine the *characterized parameters*.

2.2.5 Test Apparatus

Test apparatus **–** For the purposes of this *Recommended Practice*, the term *test apparatus* refers to the specification of the equipment needed to conduct the *characterization test*, including its configuration, power supply, controller, communications, sensors, and any means of imposing *standard conditions* (see Section 2.2.7) such as a thermal chamber or other specialized equipment, as defined for a given *device class* in Section 3.0.

2.2.6 Balance of System

Balance of System **–** For the purposes of this *Recommended Practice*, the term *balance of system* refers to the specification of either (a) characteristics of equipment that is part of the *test apparatus* or (b) *assumed parameters* and a calculation procedure, used to represent the context for the performance of the *device under test* during the *characteristics test*.

The *balance of system* can be in the form of

1. hardware that is part of the *test apparatus* and used in the *characterization test*
2. assumed parameters describing the performance of the *balance of system* that is used in the form of an emulation as part of the *characterization test.*

Examples of *balance of system* are

- assumed parameters describing the thermal performance of a building being space conditioned in order to compute the *response duration* for air conditioning *devices*
- thermal properties of the enclosure around a battery and the equipment used to maintain proper temperatures for battery operation
- characteristics of a hydrogen storage tank (size, pressurization equipment, and controls), that is either part of the *test apparatus* or is emulated when testing a fuel cell or an electrolyzer *device.*

2.2.7 Standard Conditions

Standard Conditions – For the purposes of this *Recommended Practice*, the term *standard conditions* refers to the boundary conditions that are specified as part of the *characterization test* and are imposed on the *device under test* by the test apparatus.

Examples include standard assumptions about

- outdoor temperature and other weather conditions needed by many *device classes*
- indoor air temperatures needed by air conditioning and water heater *device classes*
- the pattern of hot water draw needed by the water heater *device class*
- the energy required to recharge an electric vehicle after driving, needed by the electric vehicle charger *device class*.

2.3 Device Model-Related Definitions

This section defines various terms used to describe how a model of a *device* is translated into a generic model of a fleet of identical *devices*, patterned after a battery. The generic model is defined by a set of nameplate parameters and variables that are passed between it and the model of the fleet of *devices*.

Additional terms, parameters, and variables are defined to model *devices* for each specific *device class* in Section 3.0 of the *Recommended Practice*.

2.3.1 Device Fleet

Device Fleet – For the purposes of the *Recommended Practice*, the term *device fleet* refers to the aggregate performance of a population of *devices* identical to the *device under test*, scaled to the magnitude of the *grid service* (see *scaling factor* defined in Section 2.5.5).

The notion of a *device fleet* stems from *devices* that cannot individually meet the *eligibility requirements* of a *grid service*. That can occur when a *device under test* is only capable of *discrete responses* or is otherwise limited in its availability in ways that may not allow it to supply a *grid service* with the required fidelity. It also occurs when the *device under test* offers power for a *grid service* in quantities less than the required magnitude. Many *grid services* are defined in such a way that *response* from aggregations of small *devices* are explicitly allowed.

2.3.2 Device Model

Device Model – For the purposes of this *Recommended Practice*, the term *device model* refers to the engineering model of a *device fleet* based on the *characterized*, *adopted*, and *assumed parameters* for the *device under test*, and behavioral/usage assumptions that are specific to each *device class* and defined in Section 3.0.

2.3.3 Nameplate Parameters

Nameplate Parameters – Recognizing that the standard conditions are implicit in the characterized parameters of the *device under test*, for the purposes of this *Recommended Practice*, the term *nameplate parameters* refers to the characterized and adopted parameters from the characterization test.

2.3.4 Variables

Variables – Recognizing that the *nameplate parameters* determined for the *device under test* are tied to the *balance of plant* and *standard conditions* of the *characterization test*, and so are not constant in practice under varying conditions, for the purposes of this *Recommended Practice* the term *variables* refers to the time-series values representing the average *device* in a *device fleet*.

A number of *variables* correspond to *nameplate parameters*. However, the *variables* represent the condition of the average *device* in a *device fleet* as it changes over time. This is a subtle but important distinction.

In the case of *devices* with *discrete responses*, the *device model* may need to account for the fraction of the *device fleet* that is in each of the *relevant modes* in order to determine the *maximum* and *minimum real* and/or *reactive power for services* variables. For example, *devices* that involve refrigeration cycles (air conditioners, chillers, heat pumps, heat pump water heaters, refrigerators, and commercial refrigeration systems) may not be able to change from “on” to “off” mode for a short time after beginning an “on” mode, and vice versa, shortly after changing from “off” to an “on” mode. These “locked-out” modes reduce the power available from the *device fleet* for supplying *grid services*.

In the case of *devices* with *continuously variable responses*, similar issues arise if, for example, it is preferable for a type of battery to have deeper rather than shallow cycles, so the *device model* utilizes as few batteries as possible to provide a *grid service* at any given time. If this is the case, the *energy stored* represents the average for the *device fleet* rather than that of any individual *device*.

2.3.5 Balance-of-System Assumptions

As with the *characterization test*, assumptions about parameters describing the *balance of system* may be used to represent the context for the performance of the *device under test* needed by the *device model*.

The *balance-of-system assumptions* used in the d*evice model* for a *device class* may differ from those used in the *characterization test* as defined in Section 3.0.

2.3.6 Usage Assumptions

Usage Assumptions **–** For the purposes of this *Recommended Practice*, the term *usage assumption* refers to the assumed temporal pattern of use driving any energy consumption for a *device class* that forms the base case for comparison with the impact of providing *grid services*, as defined in Section 3.0.

The pattern reflected in a *usage assumption* reflects standard time-series assumptions about diurnal, weekly, and seasonal variations in use of the *device class* in terms of, for example,

- the power required to serve an end-use load (in kW)
- the indoor air temperature of a building that drives space conditioning loads (in °F)
- the consumption of hot water that drives a water heater (in gallons)
- the timing, and energy consumed (in kWh), of an electric vehicle’s driving pattern.

All usage assumption patterns must be mappable to an annual time series for a *grid service* to dispatch a fleet of devices like the *device under test* and compute its *performance* and *impact metrics*.

The *usage assumptions* used in the d*evice model* for a *device class* may differ from those used in the *characterization test* as defined in Section 3.0.

2.3.7 Behavioral Parameters

Behavioral Parameters – For the purposes of this *Recommended Practice*, the term *behavioral parameters* refers to assumed parameters for a *device class*, as defined in Section 3.0, generally describing human behavior that affects the *device's* ability to provide *grid services*. Examples include

- responsiveness to changes in electricity price
- maximum allowable temperature excursion from the set point in a building, a water heater, a refrigerator
- maximum duration for or times of day at which conditions may be held at the maximum temperature excursion before normal conditions must be restored
- water heater set point
- time(s) of day at which an electric vehicle must be fully charged.

The *behavioral parameters* used in the *device model* for a *device class* may differ from corresponding *assumed parameters* of the *characterization test* for the *device class*.

2.4 Battery-Equivalent Model-Related Definitions

2.4.1 Battery-Equivalent Model

Battery-Equivalent Model – For the purposes of this *Recommended Practice*, the term *battery-equivalent model* refers to an expression of a *device model* in terms commonly used to describe a battery/inverter *device*, extended as necessary to generically describe *device classes* in the *Recommended Practice*.

2.4.2 Energy Balance for a Generic Device Fleet

The energy balance and sign conventions for a generic DER *device fleet* are illustrated in Figure 2.1.

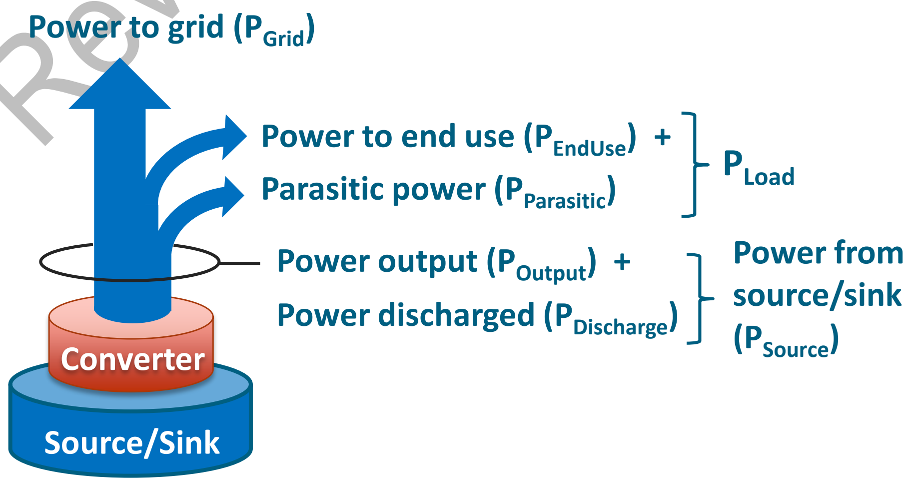

Figure 2.1. Energy Balance and Power Flows in a Generic *Device Fleet*

For the purposes of this Recommended Practice, the following variable parameters are defined for the battery-equivalent model:

1. ***Power Output*** **–** the term *power from source* refers to the AC power delivered from the *device fleet's* generators, after any conversion losses from the form of energy generated by the *devices*, and is denoted by $P_{Output}(t)$
2. ***Power Discharged***– the term *power discharged* refers to the AC power delivered from the *device fleet's* storage, after any conversion losses from the form of energy stored by the devices, and is denoted by $P_{Source}(t)$
3. ***Power from Source*** **–** the term *power from source* refers to the AC power delivered from the *device fleet's* storage or generator, after any conversion losses from the form of energy stored or generated by the *device*, and is denoted by $P_{Source}(t)$:

$$P_{Source}(t) \; = \; P_{Output}(t) \; + \; P_{Discharge}(t) \qquad (2.1)$$

4. ***Power to End Use*** **–** the term *power to end use* refers to the AC power consumed by the *device fleet* itself to any *service load* the *device fleet* is obligated to meet in order to maintain the *device's* current state of charge as defined in Section 3.0, and is denoted by $P_{Enduse}(t)$
5. ***Parasitic Power*** **–** the term *parasitic power* refers to any AC power consumed by the *device fleet* that is required to maintain the *device fleet's* current state of charge as defined in Section 3.0—for example, to provide power to keep the *device fleet* within proper operating temperature range—and is denoted by $P_{Parasitic}(t)$
6. ***Power to Load*** **–** the term *power to load* is denoted by $P_{Load}(t)$, and refers to the power required to keep the *device fleet* at its current state of charge, which is the sum of the *power to end use* and *parasitic power* for the *device fleet*:

$$P_{Load}(t) \; = \; P_{Enduse}(t) \; + \; P_{Parasitic}(t) \qquad (2.2)$$

7. ***Power Injected into Grid*** **–** the term *power injected into grid* by the device fleet, denoted by $P_{Grid}(t)$, refers to the difference between the *device fleet's power from source* and its *power to load*:

$$P_{Grid}(t) = \; P_{Source}(t) \; - \; P_{Load}(t) \qquad (2.3)$$

Or, by substitution of Equation (2.1) for $P_{Source}(t)$ and Equation (2.2) for $P_{Load}(t)$ in Equation (2.3),

$$P_{Grid}(t) = \; P_{Output}(t) + \; P_{Discharge}(t) \; - \; P_{Enduse}(t) \; - \; P_{Parastic}(t) \qquad (2.4)$$

2.4.3 Power Supplied by Device Fleet for Grid Service

Power for Service **–** For the purposes of this *Recommended Practice* in the *battery-equivalent model*, the term *power for service* from a *device fleet* is denoted by $P_{Service}(t)$ and refers to the difference between the electric power injected into the grid by the fleet when providing the *grid service* ($P_{Grid}(t)$) and the power injected into the grid when no service is being provided, i.e., the base case, denoted by $P_{GridBase}(t)$:

$$P_{Service}(t) \; = \; P_{Grid}(t) \; - \; P_{GridBase}(t) \qquad (2.5)$$

at all times(t) when a *grid service* is being provided. When a *grid service* is not being provided, $P_{Service}(t)$ is defined as zero and Equation (2.5) does not hold, because the *device class* may be recharging in which case $P_{Grid}(t) \neq P_{GridBase}(t)$.

Substituting Equation (2.3) in both terms but retaining the subscript (*Base*) indicating base-case conditions,

$$P_{Service}(t) = [P_{Source}(t) - P_{Load}(t)] - [P_{SourceBase}(t) - P_{LoadBase}(t)] \quad (2.6)$$

at all times(t) when a *grid service* is being provided; otherwise $P_{Service}(t)$ is zero.

Substituting Equation (2.1) for $P_{Source}(t)$ and Equation (2.2) for $P_{Load}(t)$ in Equation (2.6),

$$P_{Service}(t) = \left[P_{Discharge}(t) - P_{DischargeBase}(t)\right] + \left[P_{Output}(t) - P_{OutputBase}(t)\right] - \\ [P_{Enduse}(t) - P_{EnduseBase}(t)] - [P_{Parastic}(t) - P_{ParasiticBase}(t)] \quad (2.7)$$

at all times(t) when a *grid service* is being provided; otherwise $P_{Service}(t)$ is zero.

Using the operator ∆ to represent the difference between the actual power and the base-case power, Equation (2.7)**Error! Reference source not found.** is reduced to

$$P_{Service}(t) = \Delta P_{Discharge}(t) + \Delta P_{Output}(t) - \Delta P_{Enduse}(t) - \Delta P_{Parasitic}(t) \quad (2.8)$$

at all times(t) when a *grid service* is being provided; otherwise $P_{Service}(t)$ is zero.

Noting that the last two terms (including the minus signs) represent the *power conserved* by the *device fleet* in the course of providing the *grid service*, denoted by $\Delta P_{Conserved}(t)$, and reflect any change in the *end use* or *parasitic load*s due to changed operational conditions as the *device* fleet responds, we can write

$$P_{Service}(t) = \Delta P_{Discharge}(t) + \Delta P_{Output}(t) + \Delta P_{Conserved}(t) \quad (2.9)$$

at all times(t) when a *grid service* is being provided; otherwise $P_{Service}(t)$ is zero.

The *power conserved* represents, for example, reduced need to heat a battery under cold conditions if it is actively being charged, or reduced air conditioning load when the indoor air temperature is higher than in the base case. Note that the *power conserved* can be either positive or negative depending on the situation.

Thus, the *power for service* is sum of the increase in the power discharged from storage plus the increase in power output from distributed generation plus the power conserved in the course of providing the service, compared to the base case. Note that the *power for service* can be positive or negative since some *grid services* require that it be negative.

2.4.4 Services Involving Reactive Power

For services including reactive power, the variable $Q(t)$ may be substituted for the variable $P(t)$ in any of Equations (2.1) through (2.9).

2.4.5 Battery-Equivalent Model Nameplate Parameters and Variables

Battery-Equivalent Model Nameplate Parameters and Variables – For the purposes of this *Recommended Practice*, the *nameplate parameters* and *variables* of the *battery-equivalent model* of a *device fleet* are defined in Table 2.1, including *variables* defined in Sections 2.4.2 and 2.4.3 for convenience. *Nameplate parameters* are distinguished by the inclusion of an asterisk at the end of the name used in the equations.

2.4.6 Summary of Battery-Equivalent Model Characteristics

For convenience, a summary of the key characteristics of the *battery-equivalent model* for various *device classes* in provided in Table 2.2 to further the understanding of how *device classes* can be represented. How the *device model* for each *device class* represents itself as a *battery-equivalent model* is formally defined in Section 3.0.

Table 2.1. Definitions of the *Battery-Equivalent Model Nameplate Parameters* and *Variables*

Parameter	Definition	Units	Name-plate	Variable
Nameplate Parameters with Associated Variables				
Energy storage capacity	Potential energy capacity of storage (prior to conversion to AC) when the state of charge (SoC) changes from 100% to 0%	kWh	C^*	$C(t)$
Maximum real power for services	Maximum real power deliverable for *grid services*	kW	P_{max}^*	$P_{max}(t)$
Minimum real power for services	Minimum real power deliverable for *grid services* (may be <0)	kW	P_{min}^*	$P_{min}(t)$
Maximum reactive power for services	Maximum reactive power deliverable for *grid services*	kvar	Q_{max}^*	$Q_{max}(t)$
Minimum reactive power for services	Minimum reactive power deliverable for *grid services*	kvar	Q_{min}^*	$Q_{min}(t)$
Ramp rate real power up	Maximum rate of increase of real power output to the grid	kW/s	dP_{up}/dt^*	$dP_{up}/dt(t)$
Ramp rate real power down	Maximum rate of decrease of real power output to the grid	kW/s	dP_{down}/dt^*	$dP_{down}/dt(t)$
Ramp rate reactive power up	Maximum rate of increase of reactive power output to the grid	kvar/s	dQ_{up}/dt^*	$dQ_{up}/dt(t)$
Ramp rate reactive power down	Maximum rate of decrease of reactive power output to the grid	kvar/s	dQ_{down}/dt^*	$dQ_{down}/dt(t)$
Charging efficiency	Fraction of energy supplied by the grid that is stored	%	e_{in}^*	$e_{in}(t)$
Discharging efficiency	Fraction of energy drawn from storage that is delivered to the grid	%	e_{out}^*	$e_{out}(t)$
Variables Only				
Energy stored	Available energy stored in the storage media	kWh	–	$E(t)$
Power discharged from storage, real	Real power withdrawn from storage and converted to AC	kW	–	$P_{Discharge}(t)$
Power discharged from storage, reactive	Reactive power withdrawn from storage and converted to AC	kvar	–	$Q_{Discharge}(t)$
Power output from generator, real	Real power withdrawn from storage and converted to AC	kW	–	$P_{Output}(t)$
Power output from generator, reactive	Reactive power withdrawn from storage and converted to AC	kvar	–	$Q_{Output}(t)$

Parameter	Definition	Units	Name-plate	Variable
Power injected into grid, real	Real power being output to the grid while providing a *grid service* (for loads $P_{Grid}(t)$ will always be negative)	kW	–	$P_{Grid}(t)$
Power injected into grid, reactive	Reactive power being output to the grid while providing a *grid service*	kvar	–	$Q_{Grid}(t)$
Power injected into grid, real, (base case)	Real power being output to the grid while not providing a *grid service* (for loads $P_{Grid}(t)$ will always be negative)	kW	–	$P_{GridBase}(t)$
Power injected into grid, reactive, (bae case)	Reactive power being output to the grid while not providing a *grid service*	kvar	–	$Q_{GridBase}(t)$
Power delivered for service, real	Real power being delivered for a service	kW	–	$P_{Service}(t)$
Power delivered for service, reactive	Reactive power delivered for a service	kvar	–	$Q_{Service}(t)$
Load	Power that must be supplied by the grid to maintain current SoC under actual conditions, i.e., the sum of any end-use load served and any parasitic load for the device class while providing a service	kW	–	$P_{LoadBase}(t)$
Base load	Power that would have been supplied by the grid to maintain initial SoC under "no response" conditions, i.e., the sum of any end-use load served and any parasitic load for the device class in the base case (not providing a service)	kW	–	$P_{Load}(t)$
Behavioral Parameters				
Time limit, hold	Maximum duration of "hold state" for SoC at other than initial condition	hours		Δt_{hold}
Time, restoration	Time of day at which the initial SoC condition must be restored	hour of day		$t_{restore}$
Strike price	Price/incentive threshold at which a *device* initiates response to price	$/kWh	–	$SP(t)$
Price elasticity	Response rate to prices/incentives (i.e., ~ percent change in output / $/kWh)	–	–	TBD

Table 2.2. Characteristics of the *Battery-Equivalent Model* for Various *Device Classes*

Battery-Equivalent Characteristic	Battery / Inverter	Electric Vehicle (Charge/ Discharge)	PV Solar / Inverter	Fuel Cell / Inverter	Electrolyzer
Source / Sink	DC electricity in chemical battery	(see Battery)	PV array	Hydrogen storage tank (gas or liquid)	(see Fuel Cell)
Energy Storage Capacity (C)	Rated DC *energy storage capacity* of battery	(see Battery)	NA (infinite)	Energy of H_2 in tank	(see Fuel Cell)
State of Charge (SoC)	$\frac{Energy\_stored}{Energy\_capacity}$	(see Battery)	NA	X / X_{max} where X is pressure (gas) or volume (liquid) and subscript “max” indicates tank limit	(see Fuel Cell)
Converter	DC-AC inverter	(see Battery)	AC inverter	AC inverter	DC power supply
Charging Efficiency	Inverter *charging efficiency*	(see Battery)	NA	NA	DC power supply & electrolyzer efficiency
Discharging Efficiency	Inverter *discharging efficiency*	(see Battery)	(see Battery)	(see Battery)	1.0
Power to End Use	NA	TBD	NA	NA	Power to supply H_2 demand not met by discharge from storage
Parasitic Power	Battery temperature conditioning load; controls	(see Battery)	Power for controls	(see PV solar)	Power for controls and cooling liquid storage
Power Discharge	Inverter AC *power discharge* (real & reactive)	(see Battery)	NA	NA	AC power displaced by change in H_2 stored
Power Output	NA	(see Battery)	Inverter AC power discharge	(see PV solar)	NA
Power Conserved	Change in *parasitic power* compared to the base case	(see Battery)	NA	(see Battery)	(see Battery)
Power to Service	AC *power discharge* from storage, less any *power conserved*	(see Battery)	Difference in AC *power output* from *device fleet* compared to base case	(see PV solar)	Power of H_2 discharge rate from storage

Table 2.2. Characteristics of the *Battery-Equivalent* Model for Various *Device Classes* (cont.)

Battery-Equivalent Characteristic	Air Conditioner / Heat Pump (Cooling) / Chiller	Electric Water Heater	Refrigerator / Commercial Refrigeration
Source / Sink	Thermal mass of building (MC_p)	Thermal mass of water in tank (MC_p)	Thermal mass of refrigerator (MC_p)
Energy Storage Capacity (C)	$MC_p\ (T_{max} - T_{set})$, where T_{max} = max. temp. allowed by occupant T_{set} = base-case thermostat setpoint	$MC_p\ (T_{max} - T_{min})$, where T_{max} = max. temp. allowed T_{min} = min. temp. allowed	(see Air Conditioner)
State of Charge (SoC)	$\frac{(T_{max}-T_m)}{(T_{max}-T_{set})}$, where T_m = current thermal mass temp.	$\frac{(T_{tank}-T_{min})}{(T_{max}-T_{min})}$, where T_{tank} = current tank temp.	$\frac{(T_{max}-T_{refr})}{(T_{max}-T_{set})}$, where T_{refr} = current compartment air temp.
Converter	Space conditioning system	Resistive element or heat pump	Refrigeration system
Charging Efficiency	Space conditioning system coefficient of performance (COP_{sys})	1.0 (resistive) or system coefficient of performance COP_{sys} (heat pump)	Refrigeration system coefficient of performance (COP_{sys})
Discharging Efficiency	1.0	1.0	1.0
Power to End Use	AC power for steady-state load ($Load_{ss}$) at current indoor air temp. (T_{in}) and COP_{sys}: $\frac{Load_{SS}}{COP_{sys}}$	AC power to make up for hot water draw ($Load_{ss}$) at current T_{tank} and COP_{sys}: $\frac{Load_{SS}}{COP_{sys}}$	AC power to meet steady-state heat loss and content addition ($Load_{ss}$) at current T_{refr} and COP_{sys}: $\frac{Load_{SS}}{COP_{sys}}$
Parasitic Power	Power for controls	Power for tank loss; controls	Power for controls; defrost; anti-sweat; lights; etc.
Power Discharge	AC power displaced by change in energy stored: $\frac{dSoC}{dt}\ \frac{C}{COP_{sys}} = \frac{dT_m}{dt}\ \frac{MC_p}{COP_{sys}}$	AC power displaced by change in energy stored: $\frac{dSoC}{dt}\ \frac{C}{COP_{sys}} = \frac{dT_{in}}{dt}\ \frac{MC_p}{COP_{sys}}$	(see Air Conditioner)
Power Output	NA	NA	NA
Power Conserved	Change in $Load_{ss}$ due to change in T_{in} compared to base case	Change in $Load_{ss}$ due to change in T_{tank} compared to base case	Change in $Load_{ss}$ due to change in T_{refr} compared to base case
Power to Service	*Power discharge* plus *power conserved*	(see Air Conditioner)	(see Air Conditioner)

Table 2.2. Characteristics of the *Battery-Equivalent Model* for Various *Device Classes* (cont.)

Battery-Equivalent Characteristic	Thermal Energy Storage	Commercial Lighting	Electric Vehicle (Charging Only)
Source / Sink	Thermal reservoir	NA	Charging deferral
Energy Storage Capacity (C)	Capacity of thermal reservoir	NA	Energy to charge after standard use (E_{charge})
State of Charge (SoC)	Percentage of reservoir in frozen state	NA	$\frac{E_{charge} - E_{deferred}}{E_{charge}}$, where $E_{deferred}$ is the charging energy deferred
Converter	Refrigeration system	NA	DC charger
Charging Efficiency	Refrigeration system efficiency (COP_{sys})	NA	DC charger efficiency
Discharging Efficiency	1.0	NA	1.0
Power to End Use	NA (No base load defined)	AC power to lighting system	TBD
Parasitic Power	Power for controls	Power for controls	Power for controls, battery temperature conditioning, and any cabin temperature controls
Power Discharge	(see Air Conditioner)	NA	
Power Output	NA	NA	TBD
Power Conserved	NA (No base load defined)	Lighting power reduction	TBD
Power to Service	Difference between power of assumed air conditioner in balance of system and corresponding TES power	*Power conserved*	TBD

2.5 Definitions Related to Grid Services

This section defines various terms used to describe the characteristics of a *grid service* for the purposes of this *Recommended Practice*. These terms are used for each *grid service* unless otherwise specified in Section 4.0 for a specific *grid service*.

2.5.1 Grid Service

Grid Service **–** For the purposes of the *Recommended Practice*, the term *grid service* refers to the means by which a grid operator or utility motivates grid resources—central generator stations and *devices* (DERs and flexible loads)—to coordinate their operation with the utility's or grid operator's needs to keep the power grid stable, reliable, and economically efficient.

This typically involves establishing markets, incentives, or price mechanisms that compensate resources that the utility or grid operator typically does not own for modifying their behavior to effect that coordination. That is, a *grid service* is usually something for which the grid is willing to pay. In some cases, alternative noneconomic mechanisms may be involved, such as required behavior embedded in interconnection requirements for DERs, for example. Thus, it is the formal definition of the desired behavior along with the measurement and any compensation mechanisms that define a *grid service*.

When defining a *grid service*, it is useful to define the corresponding *operational objective(s*) (see definition in Section 2.5.2) that it is designed to serve, and from which the value to the grid is obtained.

2.5.2 Operational Objective

Operational Objective **–** For the purposes of the *Recommended Practice*, the term *operational objective* refers to the fundamental underlying physical needs, stated as objectives, the grid has for safe, reliable, robust, and economically efficient operation. These are often in the form of balancing supply and demand at various time scales and for various purposes.

A *grid service* is generally designed to help the utility or grid operator meet one or more *operational objectives*. Value is fundamentally created from meeting *operational objectives*, whether directly in saving capital or operational costs, or indirectly, by avoiding outages, for example. It is difficult to quantitatively value *grid services* that maintain stability or reliability, but the value, albeit indirect, is clear to all stakeholders. Many *grid services* recognize their associated *operational objective(s)* as essential and achieve them by acquiring the services from the least-cost providers via markets, for example.

When defining *grid services* in this *Recommended Practice*, we provide a short description of the *operational objective(s)* associated with them.

2.5.3 Eligibility Requirements

Eligibility Requirements **–** For the purposes of the *Recommended Practice*, the term *eligibility requirements* refers to the formal and implied requirements that *devices* must offer to be eligible to provide a *grid service*:

1. Formal *eligibility requirements* are those that the utility or grid operator specifies when defining a *grid service*. For example, some *grid services* specify classes of devices that are generally excluded from being eligible. In other cases, specific performance requirements are stated in engineering terms such as maximum time lag, minimum duration, or quality metrics.
2. Implied *eligibility requirements* are those that are not specified when a utility or grid operator defines a *grid service*. In order to inform *device* manufacturers about the general nature of the *response(s)* required of devices to provide a *grid service*, the *Recommended Practice* describes these in conjunction with defining the *grid service*. When implied *eligibility requirements* are listed for a *grid service*, some judgement is required, so implied *eligibility requirements* are informative rather than normative.

Any formal or implied *eligibility requirements* for devices to perform a given grid service are defined in Section 4.0.

2.5.4 Drive Cycle

Drive Cycle – For the purposes of the *Recommended Practice*, the term *drive cycle* refers to the representative time series of

1. the magnitude of the *grid service* in engineering units, in terms of either real or reactive power required to meet the service, as defined in Section 4.0 for each *grid service*
   a. Some *grid services* do not have a power requirement, but simply seek response to a grid condition such as price, frequency, or voltage.
2. the value of the *grid service* based on the value of the *operational objective(s)* achieved, as defined in Section 4.0 for each *grid service*
3. weather boundary conditions needed by one or more *device models* in the *Recommended Practice,* including outdoor temperature, global horizontal solar radiation, and relative humidity ($T_{out}(t)$, $G_{solar}(t)$, and $RH_{out}(t)$ in units of °F, kW/m^2, and %, respectively), as defined in Section 4.0 for each *grid service*
4. other time-series boundary conditions required to define a specific *grid service* as specified in Section 4.0 for each *grid service*. Examples include electricity price, frequency, and voltage ($Price(t)$, $f(t)$, and $V(t)$ in units of \$/kWh, Hz, and volts, respectively).

2.5.4.1 Dispatched and Simple-Response Grid Services

For the purposes of the *Recommended Practice*, *grid services* are classified as two types:

1. ***Dispatched Grid Service*** – the term *dispatched* refers to *grid services* whose *drive cycle* is based on a time series of specified power levels (real or reactive) that must be supplied by the *device fleet* if it were to entirely and exactly meet the requirements of the *grid service.* Most *grid services* in this *Recommended Practice* are *dispatched.*
2. ***Simple-Response Grid Service*** – the term *simple-response* refers to *grid services* whose *drive cycle* is based on a time series of conditions that *devices* may respond to individually, but does not define a time series of specified power levels that the *device fleet* needs to entirely and exactly meet to supply the *grid service*. Examples include self-sensed frequency and voltage time series for the artificial inertia and distribution-voltage management *grid services*, respectively. The other example is prices communicated to *devices* for the wholesale price response *grid service*.

2.5.4.2 Drive-Cycle Power

Drive-Cycle Power **–** For the purposes of the *Recommended Practice*, the term *drive-cycle power* refers to the time series of power required to supply the entire needs of a *dispatched grid service*'s *drive cycle* (*DriveCyclePower(t)*, in units of MW or Mvar for services involving real and reactive power, respectively, as defined in Section 4.0).

For *grid services* that are defined in terms of energy rather than power, the *drive-cycle power* represents the <u>average</u> power over a time-series interval.

For *simple-response grid services,* the *drive-cycle power* will have a value of “NA.”

2.5.4.3 Service Value

Service Value **–** For the purposes of the *Recommended Practice*, the term *service value* refers to the time series of value of a *grid service's drive cycle* (*Value(t)* in U.S. dollars). For example, this may represent a market price, a retail or wholesale rate, or an annual value such as capital deferral allocated in the form of a time series.

2.5.5 Scaling Factor

Scaling Factor **–** For the purposes of the *Recommended Practice*, the term *scaling factor* refers to the number of *devices* that is nominally required to supply the *grid service*, based on the nameplate power capacity for supplying services of the *device under test*, assuming the *devices* in a *device fleet* are all available at all times to supply the *grid service.*

The purpose of the *scaling factor* is to provide a rational basis for evaluating the performance of the *device fleet*. A single *device* with *discrete grid service response* may be completely inadequate and receive a “zero” metric, and a vastly oversized *device fleet* could provide the *grid service* via individual *devices* simply taking turns responding; neither scenario provides a useful basis for discriminating the performance of *devices*.

The computation of the *scaling factor* is complicated by the fact that a device may be capable of positive and/or negative *power injected into the grid*, and the *drive cycle* for a *grid service* may require positive and/or negative *power injected into the grid*. The computation of the *scaling factor* is defined in the following subsections.

2.5.5.1 Maximum Positive Drive-Cycle Power

Maximum Positive Drive-Cycle Power **–** For the purposes of the *Recommended Practice*, the term *maximum positive drive-cycle power* refers to the magnitude of the maximum positive value of the *drive-cycle power* time series, in units of MW or Mvar for services requiring real and reactive power, respectively:

$$MaxPosDriveCyclePower = \mathrm{Max}\{DriveCyclePower(t)\ Boolean(DriveCyclePower(t) > 0)\} \tag{2.10}$$

where the function Boolean() returns a time series with values of 1.0 when the logical statement is true and 0.0 when it is false. Note the *maximum positive drive-cycle power* will be zero if the *drive-cycle power* is always negative.

2.5.5.2 Maximum Negative Drive-Cycle Power

Maximum Negative Drive-Cycle Power **–** For the purposes of the *Recommended Practice*, the term *maximum negative drive-cycle power* refers to the magnitude of the maximum negative value of the *drive-cycle power* time series, in units of MW or Mvar for services requiring real and reactive power, respectively:

$$MaxNegDriveCyclePower = \mathrm{Max}\{-DriveCyclePower(t)\ Boolean(DriveCyclePower(t) < 0)\} \tag{2.11}$$

Note the *maximum negative drive-cycle power* will be zero if the *drive-cycle power* is always positive.

2.5.5.3 Computation of the Scaling Factor

For each of three possible cases of positive and/or negative maximum (P_{max}*) and minimum (P_{min}*) capacities for a *device* supplying *grid services*, the *scaling factor* (*SF)* is computed as

Case 1 – If $P_{max}* > 0$ and $P_{min}* \geq 0$, then

$$SF = \frac{MaxPosDriveCyclePower}{P_{max}{}^{*}} \tag{2.12}$$

Case 2 – If $P_{max}* \leq 0$ and $P_{min}* < 0$, then

$$SF = \frac{MaxNegDriveCyclePower}{-P_{min}{}^{*}} \tag{2.13}$$

Case 3 – If $P_{max}* > 0$ and $P_{min}* < 0$, then

$$SF = \mathrm{Max}\left\{\frac{MaxPosDriveCyclePower}{P_{max}{}^{*}},\ \frac{MaxNegDriveCyclePower}{-P_{min}{}^{*}}\right\} \tag{2.14}$$

where, in all three cases, for *grid services* requiring reactive power, Q_{max}* and Q_{min}* are substituted for P_{max}* and P_{min}*, respectively.

2.5.6 Dispatch Process for Device Fleet

For *dispatched grid services*, the *grid service* definitions in Section 4.0 will specify the procedure that each *grid* service will use to dispatch the *device fleet* to attempt to supply the *grid service's drive-cycle power*. The *device fleet* will make its availability known to the dispatch process at each time step using the parameters defined in Section 2.4.5. In general,

1. The *device model* will indicate its available power through the *maximum* and *minimum real* and/or *reactive power for services* variables, and the *energy storage capacity* and *energy stored* variables.

2. The *grid service* will then indicate to the *device model* the actual *power discharged from storage* (*real or reactive*) over the course of the *drive cycle's* time step, limited only by
    1. the requirement that the resulting *energy stored* at the end of the time step may not exceed the *energy storage capacity* nor be less than zero. (Note that the *power discharged from storage* may be less than zero when the *device fleet* is being charged).
    2. other limitations placed on the *response* such as on the timing and duration of *response* indicated by the *device model's behavioral parameters*.
3. The *device model* then advances to the next time step and updates its state variables in preparation for continuing at Step 1, including distributions of *modes* and *energy stored* for the population of *devices* in the *device fleet*.

2.5.6.1 Power Supplied for Grid Service

Power Supplied **–** for the purposes of the *Recommended Practice*, the term *power supplied* for a *grid service* refers to the time series of power actually supplied by a *device fleet* for a *dispatched grid service* by the *device fleet*, *PowerSupplied(t)*, which is

$$PowerSupplied(t) \; = \; SF \; P_{Service}(t) \qquad (2.15)$$

where $P_{Service}(t)$ is the average power supplied by the individual *devices* in the *device fleet*.

2.6 Metrics of Device Performance

2.6.1 Service Performance Metrics

This section defines the standard *service performance metrics* for devices performing a *dispatched grid service* for the purposes of this *Recommended Practice*. The standard metrics are used for each *dispatched grid service* unless otherwise specified in Section 4.0 for a specific *grid service*.

Analogous metrics are defined in Section 4.0 for each *simple-response grid service*.

2.6.1.1 Service Efficacy

Service Efficacy – For the purposes of the *Recommended Practice*, the term *service efficacy* refers to the fraction of the total energy of the *drive cycle* for a *grid service* that the *device fleet* is able to supply:

$$ServiceEfficacy \; = \frac{\sum_t |PowerSupplied(t)| \; \Delta t}{\sum_t |DriveCyclePower(t)| \; \Delta t} \qquad (2.16)$$

where the absolute value operation is required for services whose power requirement varies between positive and negative. The *service efficacy* provides a measure of the ability of a *device* to provide a *grid service*, normalized by the nameplate power capacity of the *device* by virtue of the *scaling factor*, so that the performance of *devices* of various sizes can be meaningfully compared.

2.6.1.2 **Value Efficacy**

Value Efficacy – For the purposes of the *Recommended Practice*, the term *value efficacy* refers to the fraction of the total annual value of the *drive cycle* for a *grid service* that the *device fleet* is able to supply:

$$ValueEfficacy = \frac{\sum_t |PowerSupplied(t)|\, Value(t)\, \Delta t}{\sum_t |DriveCyclePower(t)|\, Value(t)\, \Delta t} \tag{2.17}$$

The *value efficacy* provides a measure of a *device fleet's* ability to provide value (to the power grid) by providing a *grid service*, normalized by the annual value of the *grid service*, so that the potential of *devices* of various sizes can be meaningfully compared.

2.6.1.3 **Value Provided**

Value Provided – For the purposes of the *Recommended Practice*, the term *value provided* refers to the annual value ($/yr) the average *device* in a *device fleet* is able to provide for the *grid service*:

$$ValueProvided = \frac{WF}{SF} \sum_t PowerSupplied(t)|\, Value(t)\, \Delta t \tag{2.18}$$

where *WF* is a weighting factor that accounts for *grid service drive cycles* that are less than a full year in duration:

$$WF = \frac{1\,[yr]}{\sum_t \Delta t} \tag{2.19}$$

and where the denominator of Equation (2.19) is converted to units of years.

The *value provided* is a measure of the potential annual value produced (for the power grid) by a *device fleet* providing a *grid service,* and can be meaningfully compared to the *device's* cost or marginal cost. Note that the *value provided* is simply the numerator of Equation (2.17).

2.6.1.4 **Total Service Efficacy**

Total Service Efficacy – For the purposes of the *Recommended Practice*, the term *service efficacy* refers to the fraction of the total energy of the *drive cycles* for all the (*n*) *grid services* in the *Recommended Practice* that the *device fleet* was able to supply:

$$TotalServiceEfficacy = \frac{\sum_n \sum_t |PowerSupplied_n(t)|\, \Delta t}{\sum_n \sum_t |ServicePower_n(t)|\, \Delta t} \tag{2.20}$$

The *total service efficacy* is computed as the sum of the energy supplied by a *device fleet* across all (*n*) *grid services* divided by the sum energy required for all (*n*) *grid services*. It is a measure of how well the *device under test* can provide <u>all</u> the *grid services*, which allows the overall performance of *devices* of various sizes to be meaningfully compared.

2.6.1.5 Total Value Efficacy

Total Value Efficacy **–** For the purposes of the *Recommended Practice*, the term *value efficacy* refers to the fraction of the total value of the *drive cycle* for *grid service (n)* that the *device fleet* is able to supply:

$$Total\_ValueEfficacy = \frac{\sum_n \sum_t PowerSupplied_n(t)|\ Value_n(t)\ \Delta t}{\sum_n \sum_t ServicePower_n(t)|\ Value_n(t)\ \Delta t} \qquad (2.21)$$

The *total value efficacy* is the sum of the value provided by a *device fleet* across all (*n*) *grid services* divided by the sum of the value for all (*n*) *grid services*. It is a measure of how well the *device under test* captures the potential value of supplying all the grid services, which allows the overall performance of *devices* of various sizes to be meaningfully compared.

2.6.1.6 Total Value Provided

Value Provided **–** For the purposes of the *Recommended Practice*, the term *total value provided* ($/yr) refers to the sum of the value provided by one *device* in a *device fleet* across all (*n*) *grid services*, and can be meaningfully compared to the *device's* cost or marginal cost.

$$TotalValueProvided_n \;=\; \sum_n ValueProvided_n \qquad (2.22)$$

2.6.2 Energy Impact Metrics

The *Recommended Practice* provides metrics for the impact of providing each *grid service* on the energy consumption and energy cost for a *device*, and an overall energy cost metric that is the simple sum of the cost metrics across all of the *grid services*. These are defined in this section.

2.6.2.1 Net Energy

Net Energy – For the purposes of the *Recommended Practice*, the term *net energy* refers to the difference in the annual energy injected into the power grid by the average *device* in a *device fleet* when providing a *grid service* and when not providing a *grid service* (the base case).

$$NetEnergy \;=\; WF\ \sum_t \left(P_{Grid}(t) - P_{GridBase}(t) \right) \Delta t \qquad (2.23)$$

2.6.2.2 Net Energy Cost

Net Energy Cost – For the purposes of the *Recommended Practice*, the term *net energy cost* refers to the difference in the cost of the annual energy injected into the power grid by the average *device* in a *device fleet* when providing a *grid service* and when not providing a *grid service* (the base case).

$$NetEnergyCost \;=\; WF\ \left[\sum_t P_{Grid}(t)\ Price(t)\ \Delta t \;-\; \sum_t P_{GridBase}(t)\ Price(t)\ \Delta t \right] \qquad (2.24)$$

where *Price(t)* is a standard time series of the electricity prices ($/kWh) assumed by the *Recommended Practice* for the purpose of computing this metric.

2.6.2.3 Fractional Increase in Net Energy

Fractional Increase in Net Energy – For the purposes of the *Recommended Practice*, the term *fractional increase in net energy* is defined as the ratio of the *net energy* consumed when providing a *grid service* to the energy consumed by the *device fleet* when not supplying a *grid service* (the base case):

$$FractionalIncreaseNetEnergy = \frac{NetEnergy}{WF\ \sum_t P_{GridBase}(t)\,\Delta t} \tag{2.25}$$

and is applicable only to *devices* having nonzero base-case *power from source* or *power to end use*. This is because it is relatively meaningless for *device classes* that would not actively consume or produce power other than for the purpose of providing *grid services*, as defined in Section 4.0. Depending on how the base case is defined for a *device class*, this may include batteries, thermal energy storage, and fuel cells.

To interpret the meaning of the *fractional increase in net energy* metric, it is useful to expand Equation (2.25) by defining the annual energy (E_X) for any power flow (P_X) as

$$E_X = WF\ \sum_t P_X(t)\,\Delta t \tag{2.26}$$

where the suffix *X* indicates any of the power flows indicated in Figure 2.1 as defined in Sections 2.4.3 and 2.4.4.

Denoting the difference in the annual energy between the case when a *device* is supplying a *grid service* to the base case when it is not as (ΔE_X),

$$\Delta E_X = WF\ \sum_t \left(P_X(t) - P_{XBase}(t)\right)\Delta t \tag{2.27}$$

then the *fractional increase in net energy* can be expressed as:

$$FractionalIncreaseNetEnergy = \frac{\Delta E_{Output} + \Delta E_{Discharge} + \Delta E_{Enduse} + \Delta E_{Parasitic}}{E_{OutputBase} + E_{DischargeBase} + E_{EnduseBase} + E_{ParasiticBase}} \tag{2.28}$$

Loads – for *devices* that are loads, $E_{Output}(t)$ is zero by definition, as is the base-case $E_{Discharge}(t)$, so the *fractional increase in net energy* reflects the fractional increase in the energy consumed by the *device* compared to the base case:

$$\text{For load: } FractionalIncreaseNetEnergy = \frac{\Delta E_{Discharge} + \Delta E_{Enduse} + \Delta E_{Parasitic}}{E_{EnduseBase} + E_{ParasiticBase}} \tag{2.29}$$

which may be due to any effect on the *device* operation including change in its

- energy conversion efficiency when storing (charging) and discharging energy
- end-use consumption itself (due to changes in indoor air temperatures for air conditioners, for example)
- parasitic power consumption (due to changes in indoor air temperatures, for water heaters, for example).

Generators – for *devices* that are generators, $E_{Discharge}(t)$, $E_{Enduse}(t)$ and $E_{Parasitic}(t)$ are zero by definition, so the *fractional increase in net energy* reflects the fractional increase in the power output compared to the base case:

$$\text{For generators: } FractionalIncreaseNetEnergy = \frac{\Delta E_{Output}}{E_{OutputBase}} \tag{2.30}$$

which may be due a change in the system efficiency and/or *power output* from the generator when providing a *grid service* compared to its base-case operation. Note that the *fractional increase in net energy* is only meaningful when the *device* is assumed to generate during base-case operations defined in Section 4.0 (such as for PV solar *devices*).

Storage – for *devices* that store energy, $E_{Output}(t)$ and $E_{Enduse}(t)$ are zero by definition, as is the base-case $E_{Discharge}(t)$, so the *fractional increase in net energy* reflects the fractional increase in the energy consumed by the *device* compared to the base case:

$$\text{For storage: } FractionalIncreaseNetEnergy = \frac{\Delta E_{Discharge} + \Delta E_{Parasitic}}{E_{ParasiticBase}} \tag{2.31}$$

which illustrates why it is not useful as an energy impact metric for storage *devices*.

2.6.2.4 Round Trip Efficiency for Storage

Round Trip Efficiency – For the purposes of the *Recommended Practice*, the term *round trip efficiency* is defined for *device classes* that only store energy (batteries/inverters) and refers to the ratio of the annual energy input into storage to the annual energy output from storage:

$$RoundTripEfficiency = \frac{\sum_t P_{Discharge}(t)\; Boolean\big(P_{Discharge}(t)<0\big)\,\Delta t}{\sum_t P_{Discharge}(t)\; Boolean\big(P_{Discharge}(t)>0\big)\,\Delta t} \tag{2.32}$$

2.6.3 End-User Impact Metrics

End-User Impact Metrics – For the purposes of the *Recommended Practice*, the term *end-user impact metrics* refers to metrics of impacts on normal consumer amenities, other than value or energy costs, that are expected from a *device* class as defined in Section 3.0 for each *device class*.

An example is the number of degrees and duration of higher-than-normal indoor air temperatures that may occur when an air conditioner is responding to provide a *grid service*.

2.6.4 Equipment Impact Metrics

Equipment Impact Metrics – For the purposes of the *Recommended Practice*, the term *equipment impact metrics* refers to metrics of potential impacts on the equipment or controls of a *device*, as defined in Section 3.0 for each *device class*, from which manufacturers can make their own independent estimates on the lifetime or maintenance costs.

Examples include any change in the number of on/off or charge/discharge cycles a *device* undergoes per year as a result of providing a *grid service*, and any change in the distributions of on/off cycles' durations or the rate and depth of charge/discharge cycles.

[Chapters 3 and 4 are still under construction. The section headings are provided for context.]

3.0 Device Characterization Protocols and Models

3.1 Residential Air Conditioner or Heat Pump Systems with Thermostat

3.2 Residential Water Heaters

3.3 Residential Refrigerators

3.4 Commercial Rooftop Heating, Ventilation, and Air Conditioning Systems with Thermostat

3.5 Chillers

3.6 Commercial Refrigeration Systems

3.7 Networked Commercial Building Lighting Control Systems

3.8 Electrolyzers/Hydrogen Storage Systems

3.9 Battery/Inverter Systems

3.10 Electric Vehicle/Charger Systems

3.11 Thermal Energy Storage Systems

3.12 Photovoltaic Solar/Inverter Systems

3.13 Fuel Cell/Inverter Systems

4.0 Grid Service Definitions and Performance Metrics

4.1 Peak Capacity Management

4.2 Energy Market Price Response

4.3 Regulation

4.4 Spinning Reserve

4.5 Ramping

4.6 Artificial Inertia

4.7 Distribution Voltage Management

5.0 Annexure

5.1 Autonomous Grid Service Responses

6.0 References

GRID
MODERNIZATION
LABORATORY
CONSORTIUM
U.S. Department of Energy

https://gridmod.labworks.org/