Grid Services from DER Device Fleets: Volume 1 – Battery-Equivalent Models of Devices and Fleets

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Abstract

This project aims to enable a broad range of devices – principally distributed energy resources (DERs) – to provide much of the operational flexibility required by the power grid in the form of a growing number of increasingly valuable services at the bulk system and local distribution levels. To achieve this goal standard methods are needed for modeling the ability of individual devices of various classes to respond to provide grid services. This report details a general, standard device model with a battery equivalent interface applicable to each device class. This model is designed to be modular and readily incorporated in grid planning and operational tools. The functional objectives, requirements and architecture for the modeling framework are presented along with example model instantiations for eight different DERs.

Summary

The goal of this project was to enable a broad range of devices – principally distributed energy resources (DERs) – to provide much of the operational flexibility required by the power grid in the form of a growing number of increasingly valuable services at the bulk system and local distribution levels. To do this, the project focuses on developing standard methods for modeling the ability of individual devices of various classes to respond to provide grid services.

DER devices include responsive load-serving equipment and appliances in buildings (for example: air conditioning, water heaters, and refrigeration), battery storage, electric vehicle chargers, smart inverters for solar photovoltaics (PV), and fuel cells and electrolyzers.

Existing grid services include ancillary services (regulation, reserves, ramping) that keep the grid in supply-demand balance, managing peak loads to reduce infrastructure capacity requirements, and managing wholesale purchase and production costs. Industry has also envisioned new reliability services from DERs such as artificial inertia and participation in remedial action schemes that enhance the reliability and stability of the bulk grid and new distribution-level services such as mitigating rapid voltage changes and reverse power flows from high solar PV penetrations.

As its primary technical goal, ***this project provides a general, standard device model with a battery equivalent interface applicable to each device class.*** This will be in the form of an equivalent battery model, useful for comparing and aggregating the capabilities of devices from different classes and extrapolating their ability to perform grid services. This model is designed to be modular and readily incorporated in grid planning and operational tools. It is simple and generic to use, representing all device types together with only a single, simple dispatch algorithm for each grid service, rather than a custom algorithm for each device class. Such a model of DER devices is required for the tools used to plan and design new and modernized grid infrastructure, and to operate transmission- and distribution-level grid management/control systems and markets, so they can properly represent the roles and functions of DERs in the future grid.

The reporting of this project is divided into two volumes. This report (Volume 1) provides a detailed formulation and documentation of the standard device model and battery equivalent interface, along with detailed documentation on the device models for eight different DERs (water heaters, electric vehicles, batteries, photovoltaic solar panels, fuel cells, electrolzyers, residential air conditioning, and commercial refrigeration). Volume 2 presents a trial analysis of how well those DERs can provide various grid services (GMLC 2020).

This report describes the Battery-Equivalent Model, associated terms, device classes, grid services, intended benefits to users, functional objectives for the models, and the instantiation and release strategy for the models. It also presents the overall fleet and device modeling architecture and framework, general device features and explicit definitions and conventions related to the Battery-Equivalent model programming.

Detailed description of the device model equations, parameters, boundary conditions and end use and parasitic loads, and fleet formulations are also provided for the eight following devices:

- residential electric resistance water heaters
- electric vehicles with unidirectional charging (V1G)
- PV solar arrays with inverters
- batteries with inverters

- fuel cells with inverters
- electrolyzers with hydrogen storage
- residential air conditioners and heat pumps with smart thermostat
- commercial refrigeration systems.

Developing a unified modeling approach for evaluating the performance of grid services from DER devices is the basis for achieving the project's **overall strategic outcomes:**

- Enable utilities and grid operating entities to accurately assess the contribution of DER devices at the planning and operational time scales by using models of their performance that can be incorporated into the tools used to plan and operate the grid.
- Encourage device manufacturers to add the capabilities needed to supply existing and new grid services by clearly articulating the performance characteristics required and a means for evaluating their engineering and economic potential in various regions of the nation.

The project will help improve the capability of devices to provide an increasingly valuable and broader range of grid services by completely articulating the device performance needed to supply grid services beyond those that are more common today, many of which are not well understood by device manufacturers. It also includes the ability to identify and quantify the effects of performing grid services on devices' efficiency, lifetime, and ability to provide other services to the user, so that any such negative impacts can be mitigated by improved device control or grid operational strategies.

Acronyms and Abbreviations

AC	alternating current
AFC	Alkaline Fuel Cell
AC/HP	air conditioner or heat pump
API	Application Programming Interface
CAISO	California Independent System Operator
BESS	Battery energy storage systems
BEV	Battery-electric vehicles
CEC	California Energy Commission
COP	coefficient of performance
CPC	constant power control
CRM	charge reservoir model
CTA	Consumer Technology Association
DER	distributed energy resource
DL	delay appliance load
DOD	depth of discharge
DOE	U.S. Department of Energy
EER	energy efficiency ratio
EoL	End-of-Life
ERM	energy reservoir model
EV	electric vehicle
FEC	front-end controller
GMLC	Grid Modernization Lab Consortium
HVAC	heating, ventilating, and air-conditioning system
IEEE	Institute of Electrical and Electronics Engineers
IL	increase load
IPLV	Integrated Part Load Value
ISO	independent system operator
kvar	kilovolt-ampere(s) reactive
LLC	low-level controller
LT	low temperature
MPP	maximum power point
MPPT	maximum power point tracking
MT	medium temperature
MW	megawatts(s)
NERC	North American Electric Reliability Corporation
NHTS	National Household Travel Survey

ODE	Ordinary Differential Equation
OEM	Original Equipment Manufacturer
PCC	point of common coupling
PEM	proton exchange membrane
PEMFC	proton exchange membrane fuel cell
PHEV	plug-in hybrid electric vehicle
PLR	part load ratio
PV	photovoltaic
RC	resistance-capacitance (or resistor-capacitor)
SoC	state of charge
SoH	state of health
STC	standard test condition
TCIN	Time Charge is Needed
TES	thermal energy storage
TLR	temporary load reduction
TOU	time-of-use
VA	volt-ampere(s)
var	volt-ampere(s) reactive

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1.0 Introduction

Operation of the U.S. electrical grid requires careful control and coordination of electrical generation resources to match second-by-second electrical consumption. Historically, this grid control has been developed through hierarchical control of generation resources, limited energy storage to support the grid, and primarily passive consumption of electric power. However, the desire for increased integration of renewable generation, as well as efficient, low cost distributed generation, often by non-traditional grid actors, has increased the need for grid flexibility to match generation and consumption over a wide range of time scales. Control of distributed energy resources (DERs), including solar, fuel cell and other generation, thermal and battery storage, and traditional end use devices is of interest to industry as a means to address this flexibility need, but coordinated control of the various types and the large numbers of potential distributed resources is complex and to date there is limited information of the realizable benefits and limitations of these distributed resources to address the required grid needs (referred to as “grid services”). In response to this need, the U.S. DOE Grid Modernization Laboratory Consortium (GMLC) has made understanding and integration of DERs a priority effort on the path to a more resilient, reliable, and sustainable electric grid.

This report describes the development of general, standardized, Battery-Equivalent device models for simulation of key physical devices (e.g. building cooling and service water heating equipment, electric vehicles anticipated as future DERs supporting a clean and reliable power grid. The report reflects a collaborative effort between eight national laboratories to develop these Battery-Equivalent device models and to provide a common method to interface with those models to evaluate a device or device fleet’s ability to provide grid services. The ensuing sections of this Introduction describe the project purpose and scope, and the report contents and organization.

1.1 Project Purpose and Scope

The overarching goal of the Battery-Equivalent models project is to enable and spur the deployment of a broad range of DER devices that have the ability to provide much of the flexibility required for operating a clean and reliable power grid at a reasonable cost. The required flexibility, expressed in the form of a growing number of increasingly valuable services at the bulk system and local distribution levels, is largely embodied in grid services that are provided by power plants and substations today. However, flexibility is also increasingly reflected in wholesale market products or utility programs in which DERs participate. The project objectives address a primary barrier, that is the complexity in characterizing, evaluating and comparing various classes of DERs, that limits the ability of grid operational and planning tools to assess the ability of such devices to provide these services, at scale, in the future power grid. Specifically, this project delivers a set of standardized device models that can be used by utility and grid operators, device manufacturers, and other stakeholders to better analyze and understand the capabilities of DERs to provide grid services.

The project addresses the most important device classes expected to play critical roles in a modernized grid: responsive equipment and appliances in buildings, batteries, electric vehicles, hydrogen infrastructure (fuel cells and electrolyzers), and smart inverters for photovoltaic (PV) solar and batteries.

Existing grid services include ancillary services (regulation, reserves, peak load management) that keep the grid in supply-demand balance, managing peak loads to reduce infrastructure capacity requirements, and managing wholesale purchase and production costs. Industry has also envisioned new reliability services from DERs such as artificial inertia and participation in remedial action schemes (dynamic frequency and voltage regulation) that enhance the reliability and stability of the bulk grid, and new distribution-level services such as mitigating distruptive events such as rapid voltage changes and reverse power flows from high penetrations of solar PV.

As its primary technical goal, ***the project will provide a generic, standard battery-equivalent interface applicable to device models representing a range of device classes.*** These device models will be in the form of an equivalent battery model, useful for comparing and aggregating the capabilities of devices from different classes and extrapolating their ability to perform grid services. This Battery-Equivalent Model is designed to be modular and readily incorporated in grid planning and operational tools. It is simple and generic to use, representing all device types together with only a single, simple dispatch algorithm for each grid service, rather than a custom algorithm for each device class. Such a model is required for the tools used to plan and design new and modernized grid infrastructure, to operate transmission- and distribution-level grid management/control systems and markets, and to properly take into account the roles and functions of DER devices in the future grid.

Developing a unified modeling approach for evaluating the performance of grid services from DER devices is the basis for achieving the project's **overall strategic outcomes:**

- Enable utilities and grid-operating entities to accurately assess the contribution of DER devices at the planning and operational time scales by using models of their performance that can be incorporated into the tools used to plan and operate the grid.
- Encourage device manufacturers to add the capabilities needed to supply existing and new grid services by clearly articulating the performance characteristics required and a means for evaluating their devices engineering and economic potential in various regions of the nation.

The project will help improve the capability of devices to provide an increasingly valuable and broader range of grid services by completely articulating the device performance needed to supply different grid services, many of which are not well understood by device manufacturers. It will also identify and quantify the effects of performing grid services on devices' efficiency and energy consumption, and tabulate impacts that may affect other user amenities (e.g., reduce equipment lifetime or reduce the ability of equipment to provide other intended services to the user) so that any such negative impacts can be mitigated by improved device designs or grid operational strategies.

Finally, the project encourages manufacturers to build the required capabilities into their devices at the factory, where it is far less expensive than adding them later in field retrofits by utilities or customers. This ultimately lowers the costs for devices that must ultimately be borne by the power grid, whether through purchase or incentives, and hence increases their penetration at scale.

1.2 Report Contents and Organization

Section 1.0 introduces the project, the project purpose and goals, and the scope of the effort, as well as describing the report organization. Section 2.0 describes the Battery-Equivalent Model, associated terms, device classes, grid services, intended benefits to users, functional objectives for the models, and the instantiation and release strategy for the models. Section 3.0 describes the overall fleet and device modeling architecture and framework, general device features and explicit definitions and conventions related to the Battery-Equivalent model programming.

Detailed description of the device model equations, parameters, boundary conditions and end use and parasitic loads, and fleet formulations for each device class are provided in Appendices A through H.

2.0 Terminology and Objectives

This section introduces key terms and concepts used in the remainder of this report, as well as the functional objectives in describing and evaluating Battery-Equivalent models of devices.

2.1 Definition of Terms

This document describes a Battery-Equivalent Model 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 Battery-Equivalent Model, terms are defined as follows:

- *Devices* – nontraditional power grid assets or equipment, commonly referred to as DERs (distributed energy resources), 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*. Key types of devices encompassed in the Battery-Equivalent Model are listed in Section 2.2.
- *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, grid 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 to engage solely 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 power consumption. Key grid services encompassed in the Battery-Equivalent Model are listed in Section 2.3 along with the associated operational objectives.
- *Net load* – In general, devices provide services by changing the net load on the grid—by the device consuming more or less power from the grid (responsive loads, charging batteries and EVs) or injecting more or less power into the grid (generators, discharging batteries and EVs)—that must be served by the grid's traditional assets: power plants, transmission lines, and distribution substations and feeders.
- *Battery-Equivalent Model* – A procedure by which devices and their associated controls can be evaluated for their ability to provide individual grid services through a standard interface that treats each device generically in terms of the grid request for service and the grid receipt of a response from the devices. The Battery-Equivalent Model provides a means by which a wide variety and large number of different devices can be examined individually or across multiple fleets of devices. The Battery-Equivalent Model provides a known framework to allow utilities, grid operators, DER aggregators, and other entities such as regions and states to evaluate classes of devices for different grid services envisioned and allow device manufacturers to evaluate their designs for grid interactivity using a standardized modeling approach for models of interaction with the grid. The Battery-Equivalent Model is described in more detail in Section 3.0.

2.2 Device Classes

The types of devices, i.e., *device classes*, covered in the Battery-Equivalent Model in this report are as follows:

- residential electric resistance water heaters
- electric vehicles with unidirectional charging (V1G)
- PV solar arrays with inverters
- batteries with inverters
- fuel cells with inverters
- electrolyzers with hydrogen storage
- residential air conditioners and heat pumps with smart thermostat
- commercial refrigeration systems.

The general functionality, performance requirements, and characterization and modeling procedures for each device class are provided in Section 3.0 and 4.0Appendix A through H.

2.3 Grid Services

The following are examples of important grid services to be addressed by the device models and the associated operational objectives from which their value is derived:

- **Peak capacity management –** Reduce net load, as needed, so that it never exceeds the capacity of the grid infrastructure to deliver power.
- **Autonomous frequency response –** Remain on standby, ready and able to detect when grid frequency drops (or increases) rapidly (often in response to a sudden loss of generation or load), and act to complement the grid's angular momentum and generator governor controls by instantly and autonomously decreasing (or increasing) net load (within ~1 second; less is preferred).
- **Capacity market dispatch –** 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 used as reserve capacity for extreme events lasting a few hours, and may be called upon at any time as a performance test.
- **Traditional frequency regulation –** Increase or decrease net load to restore balance between supply and demand in response to a ~2- to 4-second-interval signal from the grid operator. Frequency regulation is distinct from automous frequency response as autonomous response is solely based on device sensed frequency deviation and is the primary and fastest response to frequency deviation aiming to stabilize the frequency rather than correcting it; whereas traitional and dynamic frequency regulation services are based on responding to a signal from a system operator to balance the overall generation and load on the grid. They are used as secondary response to grid frequency deviation and used to correct the deviation.

- **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 offline (typically 15–30 minutes).
- **Dynamic frequency regulation** –This is a newer ancillary service as compared to the Traditional frequency regulation. In some markets, it is differentiated from the traditional regulation service as it requires the resources to respond faster and travel more "miles" (i.e. accumulated change of MW) during the same period...
- **Autonomous distribution voltage response** – 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).
- **Wholesale market price response** – Reduce net load when prices are high, with any associated increases in net load taking place when prices are low.

The analysis of the performance of representative device models in providing these grid services will be provided in a companion 'Analysis of Grid Services Report'. A summary of all grid services considered by the GMLC is documented in [GMLC 2017].

2.4 Intended Benefits for Grid Operators and Device Providers

The intent of the Battery-Equivalent Model is (1) to enable utilities and grid-operating entities to accurately assess the contribution of DER devices in a rapidly transforming grid and (2) to encourage device manufacturers to add the capabilities needed to supply existing and new grid services by clearly articulating the performance characteristics required and by providing a means for evaluating their engineering and economic potential in various regions of the nation.

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 primarily 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 a reasonable cost, much of this flexibility is expected to be derived from services provided by large fleets of devices in the future.

For there to be an informed and expanding marketplace for devices, grid planners and operators, load aggregators, and DER portfolio owners (such EV charging networks) 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 for providing grid services 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 of their ability to provide grid services, utilities and grid operators can design markets or other operating strategies and make decisions about 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 a lower cost than would otherwise be possible without the participation of devices.

This Battery-Equivalent Model is also intended to help manufacturers by accelerating the market adoption of devices, systems, and associated controls capable of providing grid services and will 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. The Battery-Equivalent Model will allow the marketplace to reward manufacturers via increased sales of devices with advanced capabilities, based on the quality and value of their performance.

2.5 Functional Objectives

The functional objectives of the Battery-Equivalent Model shape the general framework and technical approach it uses to characterize devices and to evaluate their ability to provide grid services. These objectives are described in the following subsections.

2.5.1 Evaluating 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 require a response in proportion to the magnitude of the request. Taken at face value, this requirement would exclude the 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, a ruling by the the Federal Energy Regulatory Commission (FERC 2018) allows wholesale markets to continue to restirict participation by resources with capacities less than 100-kW. Although much lower than many previous market restrtictions (some of which ranged up to as uch as 50 MW), these restrict the direct the partuipation of small devices such as residential loads, electric vehicles, etc. other than through aggregators.

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 <u>combination</u> 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 Battery-Equivalent Model must evaluate a device’s ability to provide a grid service as a member of a large <u>fleet</u>, 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 individual performance will be derated accordingly.

2.5.2 Device Model

The device’s physical and control parameters, based on manufacturer data, engineering assumptions, or as measured by a characterization test procedure(s), can be used to construct an engineering-based *device model*. The device model must also include the timing parameters as determined from the same possible data sources. 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'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 need to be characterized separately from the device. An example is the thermal properties of a building served by an air conditioner or a thermal energy storage (TES) system. An entity adopting this Battery-Equivalent Model 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 they 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.

2.6 Software, Device Model, and API Development

The Battery-Equivalent Model interfaces, device models, and fleet models described in this model were developed in Python 3.6. Python was selected because it is an open-source software that is freely available. Furthermore, it is widely used, especially in the modeling and analytics communities. This is due in part to the large number of open-source packages available for Python. The device and fleet models use a number of these packages including *math*, *NumPy* (for computing), *Pandas* (for data structures and data analysis tools), and *csv* (for data file reading and writing). The interface and model library developed under this project will be made openly available on GitHub (an online software repository) to other users, e.g., manufacturers, grid developers, and researchers.

3.0 Key Features of the Modeling Framework

This section describes the modeling architecture; device features, fleets, and models; and provides definitions related to the Battery-Equivalent Model.

3.1 Overview of the Modeling Architecture

The battery-equivalent expression of device models is designed to provide the capabilities required by the grid modeling community to conduct a wide variety of analyses. This design includes defining a general architecture for the relationship and information exchange between high-level grid models (e.g., models of production cost, markets, transmission operations, distribution operations, etc.), device fleet models, and individual devices or sub-fleets. The generic architecture is shown in Figure 3.1.

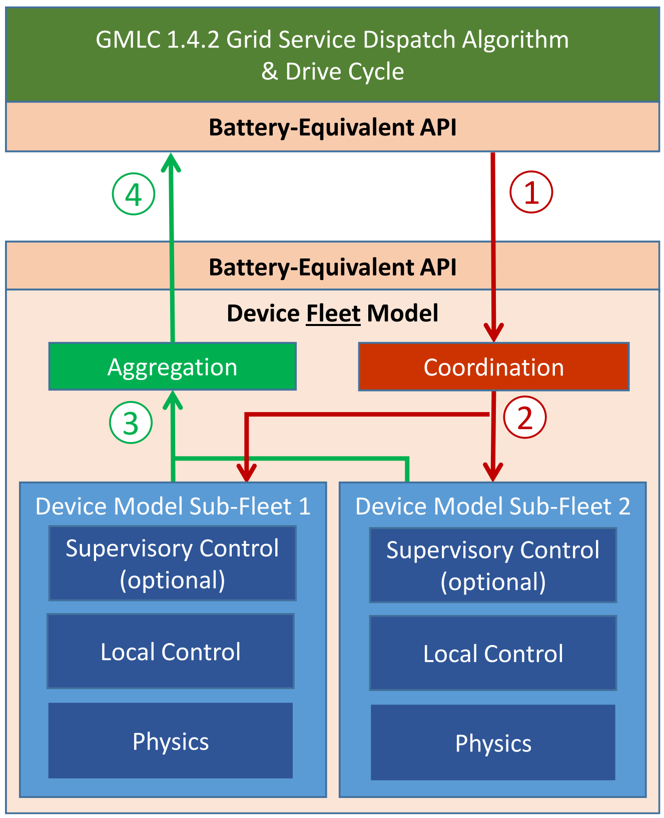

Figure 3.1. Architecture of device and device fleet models.

The green box at the top of Figure 3.1 represents a high-level grid model (e.g., a model of production cost, markets, transmission operations, distribution operations, etc.) conducting an analysis that includes the contributions of devices in supplying grid services. For the purpose of this report, the high-level grid model is simulated as the GMLC 1.4.2 Grid Service Dispatch Algorithm and associated Grid Service Drive Cycles.

In Step 1 (red circle), the high-level model makes a service request of a device fleet via the battery-equivalent API. This request includes the time step being undertaken and a request for real or reactive power delivered for the grid service (average) during the time step (from subsecond up to 1 hour depending on the service drive cycle). The high-level model makes this request with knowledge of the device fleet's power, energy, and other constraints from the previous time step (Step 4, see below).

The device fleet model (pink box) undertakes the next step of coordinating the response of each individual device or sub-fleet device. A sub-fleet device differs from an individual device only in that it has a weighting factor so that it represents a segment of the device population with identical characteristics. Fleets and the use of sub-fleet devices are defined by the analyst to represent the diversity of characteristics and states in the entire population needed to conduct a meaningful analysis. That is, they are within the purview of the high-level modeler to define.

The device fleet model developed in this project is the most general, common case of a benevolent aggregator dispatching the fleet to best deliver the service requested while minimizing any negative impacts on the devices and device owners. The aggregator is assumed to be omniscient in that it has full access to information specific to each device, i.e., all relevant variables regarding states, modes, owner limitations on use, etc. with which to understand how to allocate the request for service to individual devices, based on whether a given device can and will respond to the request for service. It may do this by distributing the request evenly to all devices able to respond, for example, or to equalize some utility or "pain" function across devices. The allocation algorithm is specific to each device class. It is also subject to modification or change in the future to reflect other allocation mechanisms devised by high-level modelers. The coordination algorithm then passes on the grid service request and time step to each device model to implement for the time step (Step 2).

In the general case, the device model has three basic elements. At the root is a physical model of the device itself, based on the characteristics supplied by the analyst. Examples of the physical modeling processes include electrical and thermal power and energy flows in a battery, or a hot water tank. Above that lies a control model that includes processes like the basic thermostat operation of a water heater's heating elements, or a battery charge controller. In the general case, above the basic control lies another layer of supervisory control, which can modify set points, within acceptable ranges defined by the analyst, to adjust the power input to or withdrawn from the grid by the device. For example, a water heater's supervisory control may raise the hot water set point to turn a water heater "off", or keep it "off". At any point during the time step, a device may balk at continuing to supply the service if its limits (specified by the high-level modeler) are exceeded. To react to a grid service request a device will most typically have a means within the local control or supervisory control that listens for grid requests as passed down through the fleet and determines an appropriate course of action to provide for an individual device response.

Although not shown in the diagram, each device model has access to a data bus containing boundary condition information for the geographical location of the device (weather) and topological location of the device (voltage). The analyst responsible for the high-level model, or the model itself, provides and updates this information as required.

Ultimately, the purpose of the device model is to calculate power provided as grid services. The difference between the device's power injection (output or negative consumption) when providing the service, compared to when it is not providing a service, defines the power provided to the service. While trivial in the case of a battery, in many device classes (particularly loads) the base case, when not providing a service, involves a level of consumption that must be modeled and tracked separately so the difference can be calculated.

Upon completion of each time step, the device model reports its average power injection and power supplied for the service to the device fleet model in Step 3. It also reports how much energy it contains at the end of the time step, and the maximum and minimum limits on power and energy it can supply in the upcoming time step. It also provides details about its throughput efficiency and constant energy losses when discharging or charging energy from its source or storage, limits on ramp rates, etc.

In Step 4, the fleet model simply aggregates the actual power supplied for the service and the limits and other variables applicable to the next time step, translates them into battery-equivalent API terms, and passes them up to the high-level model.

3.2 Key Features of Devices

3.2.1 Device

For the purposes of this Battery-Equivalent Model*,* the term *device* refers to a system comprising one or more of the following components:

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

3.2.2 Device Class

For the purposes of this Battery-Equivalent Model*,* the term *device class* refers to the family of similar devices that share

- a common engineering model and boundary conditions
- 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)
- 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
- standard assumptions about limitations or requirements placed on the device's use by its owners or users when used to provide grid services.

3.2.3 Grid Service Responses

For the purposes of the Battery-Equivalent Model, *grid service responses* refer to the way(s) in which a device adjusts its energy consumption or generation to provide grid services.

- Traditional frequency regulation – Increase or decrease net load to restore balance between supply and demand in response to a ~2- *to* 4-second-interval signal from the grid operator. Frequency regulation is distinct from autonomous frequency response as autonomous response is solely based on device sensed frequency deviation and is the primary and fastest response to frequency deviation, whereas frequency regulation services (including both traditional and dynamic) are based on responding to a signal from a system operator to balance the overall generation and load on the grid. They are used as secondary response to frequency deviation on the grid.

- ***adjust real power* –** For the purposes of the Battery-Equivalent Model, to *adjust real power* refers to increasing or decreasing a *device's* consumption or output of real power (e.g., in units of kilowatts [kW]).
- ***Dynamic*** *frequency regulation* **–**This is a newer ancillary service as compared to the Traditional frequency regulation. In some markets, it is differentiated from the traditional regulation service as it requires the resources to respond faster and travel more "miles" (i.e. accumulated change of MW) during the same period, to *adjust reactive power* refers to increasing or decreasing a *device's* consumption or output of reactive power (e.g., in units of kilovolt-ampere(s) reactive [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 on the devices action taken to respond to the request 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.

Evaluations of the ability to provide grid services using the Battery-Equivalent Model are designed to reveal these relationships.

3.2.4 Means of Response

Grid service responses can be implemented in a device through different mechanisms deemed appropriate by the manufacturer or modeler. For the purposes of the Battery-Equivalent Model, 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:

- ***mode change* –** changing a *device's* operating mode
- ***control setting change* –** changing a *device's* control setting such as a thermostat set point, an operating range, a deadband, a proportional control setting, etc.
- ***modulation* –** modulating a *device's* power consumption or generation across a continuous range. For example, setting power or speed limits on a variable speed drive.

3.2.5 Discrete and Continuously Variable Response

For the purposes of the *Battery-Equivalent Model*, *grid service responses* from a device are understood as being of the following types:

- ***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." Multi-stage devices may have more than one discrete level of real or reactive power consumption or output.

- ***continuously variable*** **–** The *device* adjusts or modulates its power consumption or generation across a continuous range.

Device classes for which the response is discrete may still be able to provide for continuously variable grid service needs in an aggregated fleet, either through a dispatch mechanism at the fleet level or other techniques where the response can be triggered differentially between the devices in the fleet.

Device models should clarify for each *grid service response* of which the *device* is capable, whether the individual device or sub-fleet device response is *discrete* or *continuously variable*.

3.2.6 Signal-Based and Autonomous Responses

For the purposes of the *Battery-Equivalent Model*, *grid service responses* are further classified as one or more of the following types:

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

Device models should indicate for each *grid service response* of which the *device* is capable, whether the individual device or sub-fleet device response is *signal-based* or *autonomous*.

3.2.7 Device Parameters

For the purposes of this *Battery-Equivalent Model*, the *characterized parameters* refer to key parameters developed through modeling assumptions, available equipment data, or characterization testing for the *device class*, that define and bound the responsiveness of the *device* and that are required to model a *device's* ability to provide any *grid service*. For example, the *characterized parameters* generally include the following, for each of the device's *relevant modes* (*m*),

- ***change in power*** **–** the amount of change in the *device'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)
- ***equipment time lag*** **–** the time lag between when the equipment (i.e., hardware) of the *device,* 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)
- ***separate controller time lag*** **–** the time lag between when any separate controller for the *device* 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)
- ***time to full response*** **–** the time lag between when the *device* 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)

- ***ramp rate*** – the rate of change of the *device'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)
- ***response duration*** – the duration of the *devices 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*
- ***energy storage capacity*** – the amount of energy that can be stored by the device
- ***charging efficiency*** – the efficiency of the *device'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*)
- ***discharging efficiency*** – the efficiency of the *device's* conversion of energy from the *device's* storage (which for some *device classes* may be part an assumed *balance of system*) to standard AC power.

Additional characterized parameters may be necessary for the development of the device model. Characterization parameters for each device class are provided in Appendices A through H.

3.3 Device Fleet and Model Features

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 within the individual model devices models for each specific device class in Appendices A through H.

3.3.1 Device Fleet

For the purposes of the Battery-Equivalent Model, the term *device fleet* refers to the aggregate performance of a population of devices of the same class as the device model.

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 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 offers power for a grid service in quantities less than the required magnitude. Many grid services are defined in such a way that responses from aggregations of small devices are explicitly allowed.

To successfully model the device fleet the diversity of the population needs to be adequately captured. This includes capturing the variation in the devices' properties, current state, usage/behavioral parameters, and boundary conditions. The devices' properties can include features such as the nameplate rating (power and capacity), control strategy, and balance-of-system attributes such as the thermal capacity of a residential building conditioned by a heat pump or AC unit. A devices' state refers to the conditions of a device at a particular point in time, and a typical example in the context of the Battery-Equivalent Model is the state of charge

(SoC). Examples manifesting as SoC include zone temperatures of a residential building, the SoC of a battery or electric vehicle, or the temperature of a hot water tank. It is important that a representative distribution be provided for a device fleet's SoC, so devices do not start off the simulation able to provide grid services in unison because they all have an identical initial condition for the SoC. Finally, devices in a fleet should simulate the variability of usage and boundary conditions seen in the real world. Examples include variability in water draw profiles for water tanks, driving patterns for electric vehicles, and thermostat set point schedules for residential homes. Variability in boundary conditions can be highly dependent on how geographically distributed the devices are. For example, within a single distribution feeder all residential homes will experience the same weather conditions. However, across a regional distribution system variability in weather conditions will need to be captured.

Sub-fleet devices – To simplify the fleet instantiation sub-fleet devices are often used to represent the contribution of devices that have identical features. These features can be discrete groupings of device parameters, attributes, or even features of the balance of system. Potential examples of sub-fleet devices include populations of water heaters that have identical tank sizes (for example, a sub-fleet device for each of the 40-, 50-, and 80-gallon tank sizes), sub-fleet devices of electric vehicles with identical manufacturer-defined charging modes, and air conditioners operating in an identical climate zone. When determining the performance of the overall fleet the weighting of each sub-fleet device is determined by the proportion of devices in the overall population that have the same sub-fleet attribute (for example, 20% of all water heaters have 40-gallon tanks). Sub-fleet devices are purely a way to aggregate the contributions of devices with an identical characteristic in a computationally efficient way. As such, use of the sub-fleet approach is optional. For example, in the current device fleet formulations, the residential electric water heater (Appendix A) does not use the sub-fleet approach, while the electric vehicles fleet model does (Appendix B).

Device model – For the purposes of this Battery-Equivalent Model, the term device model refers to the engineering model of a device fleet based on the characterized, adopted, and assumed parameters for the device and behavioral/usage assumptions that are specific to each device class.

3.3.2 Device Fleet Modes of Operation

Device fleet models can be called in three distinct ways:

- **Current time step** – This is the primary mode used to call the fleet model. In this mode the fleet model will execute from the current time step (t_0) to the next time step (t_1). The model will aim to provide the real or reactive power requested at the current time step ($P_{req}(t_0)$ or $Q_{req}(t_0)$) on average over the interval t_0 to t_1. The model will return the real and reactive power provided both as grid service and total for the time step ($P_{service}$, $Q_{service}$, $P_{injected}$ and $Q_{injected}$). The returned values will be the average powers provided for interval t_0 to t_1. If the requested power exceeds the maximum and minimum limits on power and energy the model can supply during the time step $P_{service}$ and $Q_{service}$ will not meet the requested power $P_{req}(t_0)$ or $Q_{req}(t_0)$). This typically occurs when the device hits a constraint during the time step. For example, a water heater or air-conditioning system reaches a temperature set point, an electric vehicle must commence charging in order to be fully charged by a certain time, or a battery-inverter system has a sufficient remaining SoC to deliver the requested grid service. At the end of every time step, the model computes these constraints and translates them into battery-equivalent API terms of the maximum and minimum limits on power and energy it can supply in the upcoming time step. It then passes them up to the high-level model for the next time step (t_1), which will be the new current time at the start of the next call.

- **Forecast mode –** This mode allows the high-level model to understand what level of service a device fleet could provide over a future time period. Therefore, the fleet model executes '*n*' multiple time steps (from t_0 to t_n) based on a time series of requested real or reactive power (P_{req} or Q_{req}) for that time period. (Note that '*n'* may be set to 1.) The model then returns a time series of the average real and reactive power it provided both for grid services and in total over each interval between t_0 and t_n. The model also computes and returns the constraints for each following time step (t_1 to t_{n+1}). Because this mode just provides a forecast and may then be called upon to execute in the "Current Time Step Mode" above, the model restores all state variables to those at t_0 as though the call never happened.
- **Change fleet configuration –** The third mode is used to change fleet model configurations as of the current time step (t_0). Examples include the following:
  - changing the devices desired SoC or reverting to the device's default desired SoC
  - toggling between providing real (P_{req}) or reactive power (Q_{req}) grid services as the priority of the device
  - activating the autonomous mode for the device so that it provides automatic responses based on voltage, frequency.
  - changing the frequency, voltage, or price set points for autonomous responses.

3.3.3 Nameplate Parameters

Recognizing that the standard conditions are implicit in the characterized parameters of the device model being evaluated, for the purposes of this Battery-Equivalent Model the term nameplate parameters refers to the characterized and assumed parameters for the device(s) being evaluated.

3.3.4 Variables

Recognizing that the nameplate parameters determined for the device are tied to the balance of plant and standard conditions used for the characterization of the device and so are not constant in practice under varying conditions, for the purposes of this Battery-Equivalent Model 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. For example, take the variable *energy storage capacity*. In batteries, the energy storage capacity is a common nameplate parameter describing the size of a battery (i.e., its kWh rating). However, this nameplate value is only valid for the nameplate *conditions* under which it was tested, measured, or otherwise rated. That is, it's actual energy capacity at any point in time is a function of other conditions such as the ambient temperature, as anyone who starts a car on a very cold morning experiences. It's more literally a function of the temperature of the battery's electro-chemical materials themselves, which not only vary with the ambient condition but also the batteries recent usage, since its inefficiency in charging and discharging energy heats it up. Hence, a battery is often characterized by its nameplate parameter energy storage capacity, but a highly-detailed battery model may also model and track the energy capacity as a variable as it changes over time to values somewhat above and below the nameplate value. There are numerous analagous issues in which common nameplate parameters used to describe other types of devices should be and often are tracked as variables. Care must be taken when developing and discussing specific device models to make any such potential ambiguities clear.

In the case of devices that have discrete responses, the fleet 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. 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 uses 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.

3.3.5 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.

Examples of balance of system assumptions 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.

3.3.6 Usage Assumptions

For the purposes of this Battery-Equivalent Model, 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.

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 kilowatts)
- 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 kilowatt-hours), of an electric vehicle's charging pattern.

All usage assumption patterns must be able to be mapped to an annual time series for a grid service to dispatch a fleet of devices and compute individual device performance and impact metrics.

3.3.7 Behavioral Parameters

Behavioral parameters for a device class, generally describe human behavior that affects a device's ability to provide grid services. Examples include the following:

- 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.

3.4 Definitions Related to the Battery-Equivalent Model

3.4.1 Battery-Equivalent Model

The Battery-Equivalent Model is an expression of a device model in terms commonly used to describe a battery/inverter device, extended as necessary to generically describe all the device classes listed in Section 2.2.

3.4.2 Energy Balance for a Generic Device Fleet

The energy balance and sign conventions for a generic DER device fleet are illustrated in Figure 3.2.

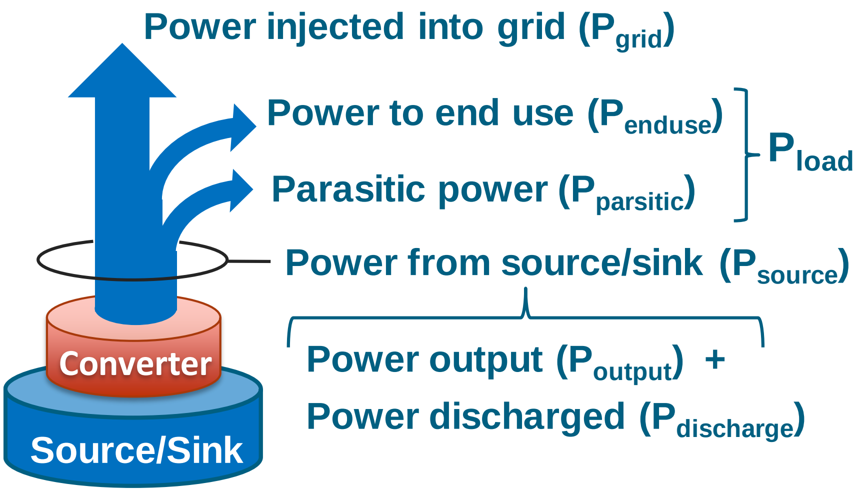

Figure 3.2. Energy balance and power flows in a generic device fleet.

The following variables are defined for the Battery-Equivalent Model:

- ***power output*** – Output power is the AC power delivered from the devices' nominal generation or consumption after any conversion losses from the form of energy generated by the devices, and is denoted by $P_{output}(t)$. Examples include the baseline power generated by a PV solar panel or the baseline energy consumed (e.g., negative output) by a heating, ventilation, and air-conditioning (HVAC) system.
- ***power discharged*** – Power discharged is 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 $P_{discharge}(t)$.
- ***power from source*** – Power from source is the AC power delivered from the device fleet's storage or generator (or both simultaneously), after any conversion losses from the form of energy stored or generated by the device, and is denoted by $P_{source}(t)$:

$$P_{source}(t) = P_{output}(t) + P_{discharge}(t) \tag{3.1}$$

- ***power to end use*** –Power to end use is the AC power consumed by the device fleet to meet any service (end use) load the device fleet is obligated to meet in order to maintain the device's current SoC, and is denoted by $P_{enduse}(t)$
- ***parasitic power*** – Parasitic power is any AC power consumed by the device fleet that is required to maintain the device fleet's current SoC—for example, to provide power to keep the device fleet within proper operating temperature range—and is denoted by $P_{parasitic}(t)$
- ***power to load*** – Power to load is denoted by $P_{load}(t)$, and is the power required to keep the device fleet at its current SoC, which is the sum of the power to end use and parasitic power for the device fleet:

$$P_{load}(t) = P_{enduse}(t) + P_{parasitic}(t) \tag{3.2}$$

- ***power to grid*** – Power to the grid from the device fleet, denoted by $P_{grid}(t)$, is the difference between the device fleet's power from source and its power to load:

$$P_{grid}(t) = P_{source}(t) - P_{load}(t) \tag{3.3}$$

Or, by substitution of Equation (3.1)

for $P_{source}(t)$ and Equation (3.2) for $P_{load}(t)$ in Equation (3.3),

$$P_{grid}(t) = P_{output}(t) + P_{discharge}(t) - P_{enduse}(t) - P_{parastic}(t) \tag{3.4}$$

3.4.3 Power Supplied by Device Fleet for Grid Service

Power for Service – Power for service from a device fleet is denoted by $P_{service}(t)$ and is 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 $P_{grid.base}(t)$, where the subscript (*.base*) is base-case conditions:

$$P_{service}(t) = P_{grid}(t) - P_{grid.base}(t) \tag{3.5}$$

at all times(t) when a grid service is being provided. When a grid service is <u>not</u> being provided, $P_{service}(t)$ is defined as zero and Equation (3.5) does not hold, because the device class may be recharging, in which case $P_{grid}(t) \neq P_{grid.base}(t)$.

Substituting Equation (3.3) in both terms:

$$P_{service}(t) = [P_{source}(t) - P_{load}(t)] - [P_{source.base}(t) - P_{load.base}(t)] \tag{3.6}$$

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

Substituting Equation (3.1) for $P_{Source}(t)$ and Equation (3.2) for $P_{Load}(t)$ in Equation (3.6):

$$P_{service}(t) = \left[P_{discharge}(t) - P_{discharge.base}(t)\right] + \left[P_{output}(t) - P_{output.base}(t)\right] - \left[P_{enduse}(t) - P_{enduse.base}(t)\right] - \left[P_{parastic}(t) - P_{parasitic.base}(t)\right] \tag{3.7}$$

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

Using the operator Δ to represent the difference between the actual power and the base-case power, Equation (3.7) is reduced to:

$$P_{service}(t) = \Delta P_{discharge}(t) + \Delta P_{output}(t) - \Delta P_{enduse}(t) - \Delta P_{parasitic}(t) \tag{3.8}$$

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 loads due to changed operational conditions as the device fleet responds, we can write:

$$P_{service}(t) = \Delta P_{discharge}(t) + \Delta P_{output}(t) + \Delta P_{conserved}(t) \tag{3.9}$$

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 the 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, because some grid services require that it be negative.

3.4.4 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 (3.1)

3.4.5 Nameplate Parameters and Variables

The nameplate parameters and variables of the Battery-Equivalent Model of a device fleet are defined in Table 3.1, which includes variables defined in Sections 3.4.2 and 3.4.3 for convenience. Nameplate parameters are distinguished from related variables by the inclusion of an asterisk at the end of the name used in the equations.

3.4.6 Summary of Battery-Equivalent Model Characteristics

For convenience, a summary of the key characteristics of the Battery-Equivalent Model for various device classes is provided in Table 3.6 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 Appendix A through H.

Table 3.1. Battery-Equivalent Model Nameplate Parameters

Parameter	Definition	Units	Name-plate
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*
Maximum power to grid (real, reactive)	Maximum power output by the device to the grid (often zero in the case of loads)	kW, kvar	$P_{grid.max}$*, $Q_{grid.max}$*
Minimum power to grid (real, reactive)	Minimum power output by the device to the grid (≤0 in the case of loads)	kW, kvar	$P_{grid.min}$*, $Q_{grid.min}$*
Maximum power for services (real, reactive)	Maximum power deliverable for grid services	kW, kvar	$P_{service.max}$*, $Q_{service.max}$*
Minimum power for services (real, reactive)	Minimum power deliverable for grid services	kW, kvar	$P_{service.min}$*, $Q_{service.min}$*
Ramp rate, power up (real, reactive)	Maximum rate of <u>increase</u> of power output to the grid	kW/s kvar/s	$\dot{P}_{up}$*, $\dot{Q}_{up}$*
Ramp rate, power down (real, reactive)	Maximum rate of <u>decrease</u> of power output to the grid	kW/s, kvar/s	$\dot{P}_{down}$*, $\dot{Q}_{down}$*
Charging efficiency	Fraction of the energy supplied to the converter that is stored	%	e_{in}*

Parameter	Definition	Units	Name-plate
Discharging efficiency	Fraction of the energy generated or drawn from storage that is transformed to useful form by the converter	%	e_{out}*
Maximum service requests	Maximum number of service requests per day (midnight to midnight)	1/day	$N^*_{req}(t_1)$

Table 3.2. Battery-Equivalent API Variables Passed from the High-Level Model to the Device Fleet (Step 1)

Parameter	Definition	Units	Variable	Python API Name
Power requested for service (real, reactive)	Power for grid service requested over the time step	kW, kvar	$P_{req}(t_0)$, $Q_{req}(t_0)$	*P_req*, *Q_req*
Time stamp	Time of grid request (i.e., the timestamp at the beginning of the period of the request	Time stamp	t_0	*Ts_req*
Length of requested simulation period	The length of the period of the request for real or reactive power to be provided to the grid	(See Note 5)	*Simstep*	*sim_step*

Notes:

1 Values of $P_{req}(t_0)$ <u>or</u> $Q_{req}(t_0)$ ≠ *None* (i.e., a real value, including 0 which is a valid request) indicate the level of real and/or reactive power being requested for a grid service. Note that if either real or reactive power is being requested, the <u>other</u> power variable $P_{req}(t_0)$ or $Q_{req}(t_0)$, should usually be set to *None* in the service request because in many circumstances a device may only be able to provide one or the other. A request with <u>both</u> $P_{req}(t_0)$ and $Q_{req}(t_0)$ as real values is a valid request, but the device will treat one or the other as the priority (see Note 3 below).

2 Values of $P_{req}(t_0)$ <u>and</u> $Q_{req}(t_0)$ = *None* indicates no grid service power is being requested and the device is free to return to default operation. ; i.e., it is allowed to return to its desired SoC. The device should report $P_{grid}(t_0)$ and $Q_{grid}(t_0)$ associated with serving any actual or parasitic load and this value should be returned to the high-level model as usual.

3 If both $P_{req}(t_0)$ <u>and</u> $Q_{req}(t_0)$ are non-zero values, the device fleet will try to provide the requested $P_{req}(t_0)$ and $Q_{req}(t_0)$. If it cannot provide for both requests it will provide one or the other based on the service request priority configuration variable $P_{priority}$ and report the resulting $P_{service}(t_0)$ and $Q_{service}(t_0)$ to the high-level model. (In general only one should be requested; the only service that we envision might ask for <u>both</u> $P_{req}(t_0)$ <u>and</u> $Q_{req}(t_0)$ would be a distribution voltage control service, where, based on the current constraints $Q_{service.max}$ and $Q_{service.min}$, the high-level model has decided $Q_{req}(t_0)$ will be insufficient to solve the voltage problem at hand.)

4 Python API names for the variables above are found in class: "fleet_request" of the Battery-Equivalent API.

5 Ts_req and sim_step use the standard Python datetime class.

Table 3.3. Battery-Equivalent API Variables Available from Topological and Geographical Information Busses

Parameter	Definition	Units	Variable
Rate for power (real, reactive)	Rate (price/incentive) for power delivered for a grid service over the time step	$/kWh, $/kvar-h	$R_{real}(t_0)$, $R_{reactive}(t_0)$
Service voltage at device	Ratio of voltage at device relative to nominal service voltage	-	$V_{ratio}(t_0)$

Parameter	Definition	Units	Variable
Outdoor temperature at device	Outdoor temperature at device	°C	$T_{out}(t_0)$
Total solar horizontal radiation at device	Total (direct + diffuse) solar horizontal radiation at device	W/m^2	$H_{solar}(t_0)$
Service water temperature	Temperature of service cold water	°C	$T_{h2o}(t_0)$
Service frequency at device	Frequency of power grid at location of device	Hz	$f(t_0)$
Others TBD			

Table 3.4. Battery-Equivalent API Variables Passed from the Device Fleet to the High-Level Model (Step 4a) for the Time Step Beginning at t_0

Parameter	Definition	Units	Variable	Python API Name
Variables below are grid service request responses for the time period beginning at t_0 and are returned to the high-level model				
Power to grid (real, reactive)	Power from the device to the grid (loads will always be zero or negative), average over the time step	kW, kvar	$P_{grid}(t_0)$, $Q_{grid}(t_0)$	*P_togrid* *Q_togrid*
Power delivered for service (real, reactive)	Power delivered for the grid service, average over the time step	kW, kvar	$P_{service}(t_0)$, $Q_{service}(t_0)$	*P_sevice* *Q_service*
Energy stored	Available energy stored in the storage media at the end of the time step	KWh	$E(t_0)$	*E*
Variables below are Battery-Equivalent API *Constraint* variables passed from the device fleet to the high-level model for the next time step (t_1)				
Energy storage capacity	Potential energy capacity of storage (prior to conversion to AC) when the state of charge (SoC) changes from 100% to 0% for the next time step	kWh	$C(t_1)$	*C*
Maximum power to grid (real, reactive)	Maximum power from the device to the grid for the next time step (may be zero in the case of loads)	kW, kvar	$P_{grid.max}(t_1)$, $Q_{grid.max}(t_1)$	*P_togrid_max* *Q_togrid_max*
Minimum power to grid (real, reactive)	Minimum power from the device to the grid for the next time step (≤0 in the case of loads)	kW, kvar	$P_{grid.min}(t_1)$, $Q_{grid.min}(t_1)$	*P_togrid_min* *Q_togrid_min*
Maximum power for service (real, reactive)	Maximum power deliverable for grid services for the next time step	kW, kvar	$P_{service.max}(t_1)$, $Q_{service.max}(t_1)$	*P_service_max* *Q_service_max*
Minimum power for service (real, reactive)	Minimum power deliverable for grid services for the next time step	kW, kvar	$P_{service.min}(t_1)$, $Q_{service.min}(t_1)$	*P_service_min* *Q_service_min*
Ramp rate, power up (real, reactive)	Maximum rate of <u>increase</u> of power output to the grid for the next time step	kW/s kvar/s	$\dot{P}_{up}(t_1)$, $\dot{Q}_{up}(t_1)$	*P_dot_up* *Q_dot_up*
Ramp rate, power down (real, reactive)	Maximum rate of <u>decrease</u> of power output to the grid for the next time step	kW/s, kvar/s	$\dot{P}_{down}(t_1)$, $\dot{Q}_{down}(t_1)$	*P_dot_down* *Q_dot_down*

Parameter	Definition	Units	Variable	Python API Name
Charging efficiency	Fraction of the energy supplied to the converter that is stored at power grid's request (or at minimum power to grid if Power Requested = "None")	%	$e_{in}(t_1)$	*Eff_charge*
Discharging efficiency	Fraction of the energy generated or drawn from storage that is transformed to useful form by the converter at the power grid's request (or at maximum power to grid if Power Requested = "None")	%	$e_{out}(t_1)$	*Eff_discharge*
Time limit, hold	Maximum duration of "hold state" for SoC at other than the desired condition	hours	$\Delta t_{hold}(t_1)$	*dt_hold_limit*
Time, restoration	Time of day at which the desired SoC condition must be restored	hour of day	$t_{restore}(t_1)$	*ts_restore*
Strike price	Energy price/incentive threshold at which device initiates response	$/kWh	$SP(t_1)$	*Strike_price*
State-of-charge cost	Incentive requirement for the device to be at SoC other than 100%	$/hr	TBD	*SOC_cost*

Notes:
1 Python API Names above can be found in the class: "fleet_response" of the Battery-Equivalent API.

Table 3.5. Other Battery-Equivalent Model's Variables (not passed through the API)

Parameter	Definition	Units	Variable
Power discharged (real, reactive)	Power withdrawn from storage and converted (as necessary) for use	kW, kvar	$P_{discharge}(t)$, $Q_{discharge}(t)$
Power output from source (real, reactive)	Power generated by the device, prior to any required AC-to-DC conversion	kW, kvar	$P_{output}(t)$, $Q_{output}(t)$
Power to grid, base case (real, reactive)	Power being output to the grid while not providing a grid service (for loads, $P_{Grid}(t)$ will always be zero or negative)	kW, kvar	$P_{grid.base}(t)$, $Q_{grid.base}(t)$
Load	Power required to maintain current SoC under actual conditions, i.e., any end-use load served plus any parasitic load for the device (while providing a service)	kW	$P_{load}(t)$
Base load	Power required to maintain initial SoC when not providing a service, i.e., any base-case end-use load served plus any base-case parasitic load for the device	kW	$P_{load.base}(t)$

Table 3.6. Characteristics of the Battery-Equivalent Model for Various Device Classes

Battery-Equivalent Character-istic	Battery/Inverter	Electric Vehicle (Charging Only)	PV Solar/Inverter	Fuel Cell/ Inverter	Electrolyzer
Source/ Sink	DC electricity in chemical battery	Charging deferral	PV array	Hydrogen storage tank (gas or liquid)	(See Fuel Cell)
Energy Storage Capacity (C)	Rated DC *energy storage capacity* of battery	Energy to charge after standard use (E_{charge})	NA (infinite)	Energy of H_2 in tank	(See Fuel Cell)
State of Charge (SoC)	$\frac{Energy\_stored}{Energy\_capacity}$	$\frac{E_{charge} - E_{deferred}}{E_{charge}}$, where $E_{deferred}$ is the charging energy deferred	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	DC charger	AC inverter	AC inverter	DC power supply
Charging Efficiency	Inverter *charging efficiency*	DC charger efficiency	NA	NA	DC power supply & electrolyzer efficiency
Discharging Efficiency	Inverter *discharging efficiency*	1.0	(See Battery)	(See Battery)	1.0
Power to End Use	NA	Power needed to meet drivers’ driving demands	NA	NA	Power to supply H_2 demand not met by discharge from storage
Parasitic Power	Battery temperature conditioning load; controls	Power for controls	Power for controls	(See PV solar)	Power for controls and cooling liquid storage
Power Discharge	Inverter AC *power discharge* (real & reactive)	NA	NA	NA	AC power displaced by change in H_2 stored
Power Output	NA	AC *power requested* to the grid	Inverter AC power discharge	(See PV solar)	NA
Power Conserved	Change in *parasitic power* compared to the base case	NA	Reduction in power for controls when PV is curtailed	(See Battery)	(see Battery)

Battery-Equivalent Character-istic	Battery/Inverter	Electric Vehicle (Charging Only)	PV Solar/Inverter	Fuel Cell/ Inverter	Electrolyzer
Power to Service	AC *power discharge* from storage, less any *power conserved*	Difference in AC *power requested* to the grid from *device fleet* compared to the baseline case	Difference in AC *power output* from *device fleet* compared to base case	(See PV solar)	Power of H_2 discharge rate from storage

Table 3.6. Characteristics of the Battery-Equivalent Model for Various Device Classes (contd.)

Battery-Equivalent Characteristic	Air Conditioner / Heat Pump (Cooling)	Electric Water Heater	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 set point	$MC_p\ (T_{max} - T_{min})$, 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)

4.0 References

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Appendix A – Residential Electric Water Heaters

A.1 Basic Device Purpose

A water heater is equipment that provides service hot water for a residence or commercial building. While there are different types of equipment that can provide this, the focus of this device model is on residential electric resistance tank water heaters. Electric resistance tank water heaters can provide grid services because the tank is able to store electrical energy as thermal energy, thereby enabling increased or decreased electric load on the grid by changing the desired temperature of the stored water. While heat pump electric storage water heaters have many characteristics that are similar to electric storage water heaters and are faced with the same loads, these features are not considered here. The capability to model heat pump water heaters will be added as part of the next phase of this project, which includes experimental characterization of the potential to provide grid services via a heat pump water heater. These data will be used to inform the heat pump water heater model. Electric tankless water heaters also exist on the market today but are not considered here because their minimal storage volume limits the opportunity to provide grid services.

A.2 Standard Controls and Normal Operational Modes

An electric storage water heater is typically equipped with two electric elements that have the same electric capacity, each controlled by their own thermostat. One element is located near the top of the tank to allow quick recovery from hot water draws and the other element is located near the bottom of the tank to allow most of the tank volume to recover to set point. The elements are usually controlled using a master-slave configuration with the upper element having priority to avoid having both elements on at the same time. While the set point temperature on most water heaters is set manually, the set point temperature can be changed by the user at any time. The heating elements in water heaters also have a deadband, which is built into the device and cannot be changed by the user. Typical values for the deadband are 10 °F and are one sided, with the set point temperature being used as the temperature at which the heating elements turn off and the set point minus the deadband used as the temperature at which the heating elements come on. For example, a water heater with a set point of 125°F and a deadband of 10°F would turn on at a temperature of 115°F and turn off at a temperature of 125°F.

Typical operational states are as follows:

- Standby – No water draw or active heating
- Active heating, no delivery – Electricity provided to one of the heating elements to reheat the tank, no water draw
- Active heating, hot water delivery – Electricity provided to one of the heating elements with simultaneous hot water draw
- No heating, hot water delivery – No electricity provided to heating elements with hot water draw occurring.

A.3 Equipment Availability and Usage Patterns

Electric resistance water heaters are typically used year round. Water is stored in the storage tanks year round, most commonly at a fixed delivery temperature controlled by the thermostat; so electric resistance water heaters should be considered to have year-round availability for use as a grid-connected device. As service water heating loads, the hot water energy delivered from the water heater will vary with each household in a different way. Because they rely on stored hot water to meet possible high hot water demand loads at any time (such as a shower), electric storage water heaters typically face many service hot water loads that are small enough that they do not trigger the heating elements (such as a short draw for hand washing). Gradual temperature reductions due to tank losses during standby could trigger the elements in a fashion non-coincident with the water use. In addition, large hot water draws that exceed the heating elements capability, resulting in temporary cooling of the average and outlet temperature in the tank significantly below the set point, can result in the heating element operating continuously for long periods in a recovery mode after the water draw has finished. Depending on the tank temperature, the water heater may not be able to accept load-add commands (because it is already at the maximum safe temperature for hot water delivery) or load-shed commands (if the tank temperature has dropped to a temperature at which the delivered hot water would not be sufficiently hot to meet the desired intent of the household user).

Because this project focused on residential electric water heaters, the usage patterns considered here are consistent with "typical" residential hot water usage and would not apply for most commercial buildings. Commercial hot water usage may be significantly different and changes significantly depending on the building type (for example, a laundromat has very different hot water usage than a school). The residential draw patterns used here were developed based on the Building America Domestic Hot Water Event Schedule Generator (available for free at: https://www.energy.gov/eere/buildings/building-america-analysis-spreadsheets). This tool creates a full year of discrete hot water usage events for each end use typically found in a home (showers, baths, sinks, clothes washers, and dishwashers). Showers, sinks, and baths are treated as mixed water use events where the homeowner tempers the hot water with mains water to reach a useful temperature (110°F as specified in the latest version of the Building America House Simulation Protocols). In this work, the tank temperature during the last time step is used as the hot water temperature for determining the mixed draw volume to avoid having to iterate between the draw volume and the final tank temperature. Clothes washer and dishwasher draws are treated as hot only events where all the water drawn comes directly from the water heater. The discrete events, when averaged over a whole year, match the typical hot water usage pattern for each end use. Draw profiles include weekday and weekend variation in hot water use and two weeks of vacation per year. An example day of hot water usage and the average residential net hot water usage (across all end uses) are shown in Figure A.1.

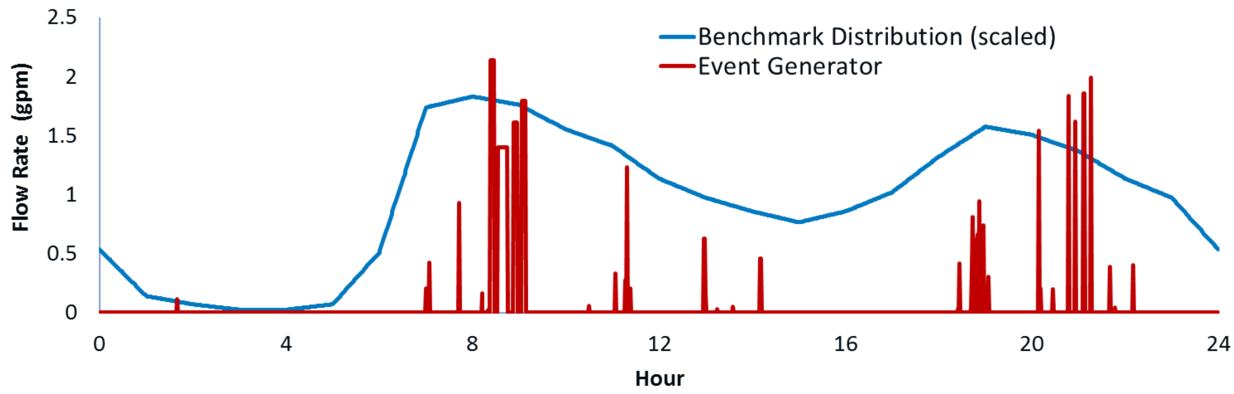

Figure A.1. Example daily hot water events from the Building America domestic hot water event schedule generator compared to average residential hot water usage.

Residential hot water use changes significantly with the number of occupants in a home. The draw profiles use the number of bedrooms in a home as a proxy for the number of occupants. In addition, the hot water drawn from the tank to meet mixed end uses varies depending on the mains water temperatures, which varies by region. On a national level, typical low usage of hot water in the home (either due to occupant behavior or the number of occupants) would average approximately 29 gal/day of hot water, a medium usage would average 60 gal/day, and high usage would average 98 gal/day (https://www.osti.gov/servlets/purl/1127143). This level of hot water usage would lead to electric resistance element on times of approximately 1.4 hr/day for low users (6.3 kWh/day), 2.0 hr/day for medium users (9.2 kWh/day), and 2.7 hr/day (12 kWh/day) for high users.

A.4 Change in Power Output Resulting from Response

A residential electric water heater is typically an on/off device from the electrical view point. Electric power draws are either full on at the rated element capacity, or full off. In the case of water heaters that can respond to grid events, there may be a small parasitic power draw for the control module (on the order of several watts, but actual power consumption can vary depending on exactly which module is used). Current grid-enabled water heaters accept a standard set of commands defined in Consumer Technology Association (CTA) Standard 2045, but it is up to the individual water heater how to respond to the command. In practice, this means that different manufacturers may respond differently to identical signals. This work is not intended to be limited to current standards, nor is it intended to favor certain standards over others; rather, this work is intended to explore the fundamental potential of water heaters for providing grid services without regard to current or proposed protocols or standards. Therefore, not every command defined in the standard is modeled here, but the focus is instead on requests to either increase or decrease load. The typical response to a request for grid services is to change the set point temperature of the water heater rather than directly activating or deactivating the electric resistance elements. Directly activating or deactivating the elements could lead to unsafe conditions (largely due to scalding risk at high temperatures) or dissatisfaction with the hot water provided due to high variability in the hot water temperature provided.

A residential water heater controller can also be developed to respond to an autonomous service request. In this mode, the change in power output resulting from a response is similar to ON and OFF power draw from the water heater elements.

A.5 Device Model

A.5.1 Assumptions

In addition to the parameter assumptions listed above, the following additional assumptions are applied to the battery-equivalent water heater model:

- Each water heater is modeled using a mixed tank rather than a stratified tank. A mixed tank assumes that the entire tank is at a single uniform temperature. In actual usage, there may be times when the tank temperature varies substantially at different heights. For example, after a moderate draw cold water is added to the bottom of the tank while the top of the tank remains hot. Using a mixed tank misses the potential impact of this but substantially decreases the run time and complexity of the water heater model.
- Because electric resistance water heaters are purely resistive loads, no reactive power is consumed and the water heater cannot respond to any requests for grid services to provide reactive power.
- While annual draw profiles have been created and included with this model, during a run the draw profile picks one week of data and repeats it for computational efficiency. The start day of the year is determined randomly at the start of the fleet initialization. There is little loss of fidelity due to water draw patterns being predominantly weekly in nature with relatively smaller seasonal impacts.
- In addition to the minimum and maximum tank temperatures imposed, a minimum state of charge (SoC) of 0.2 and maximum of 0.8 are imposed.
- For a water heater to decide to participate in a load-add event the minimum available capability must exceed 350 Wh. This is determined using the heat capacity of the water and the temperature difference between the current temperature and the maximum allowable tank temperature.
- For a water heater to decide to participate in a load-shed, the minimum available capability to shed load must exceed 150 Wh. This is determined using the heat capacity of the water and the temperature difference between the current temperature and the minimum allowable tank temperature.

A.5.2 Parameters/Equipment Characteristics

Many of the assumed parameters for an individual water heater are determined at the start of the creation of the fleet. Whenever possible, reasonable statistical distributions are assumed to provide variety for the water heater fleet. The assumed parameters and distributions are as follows:

- Water heater set point temperature – The average water heater set point temperature is 123 °F, with a standard deviation of 9.7°F. A lower limit of 110°F is applied to ensure that the water heater provides adequate hot water. The limits to tank temperature are provided in the Boundary Conditions section.

- Water heater deadband – A deadband of 10°F is assumed for all water heaters.
- Water heater volume – 20% of water heaters have a rated volume of 40 gallons, 70% of water heaters have a rated volume of 50 gallons, and 10% have a volume of 80 gallons.
- Element capacity – The element capacity for all water heaters is assumed to be 4.5 kW.
- Tank heat loss coefficient – All water heaters are assumed to have a heat loss coefficient of 10 W/K. This level corresponds to a typical efficiency level (Uniform Energy Factor of 0.92).

A.5.3 Boundary Conditions

The boundary conditions considered in this model are as follows:

- Temperature – When changing the set point to provide grid services, the minimum allowed tank temperature is 105°F and the maximum allowed temperature is 160°F.
- Location – Space temperatures are taken from results of a run of BEopt. Currently all simulations are assumed to be run in Denver, but other locations could be added by performing additional simulations. In terms of the installation location in the home, 67% of water heaters are assumed to be installed in unconditioned space and 33% are assumed to be installed in conditioned space.
- Main water temperature – This is calculated from the same BEopt simulation used to calculate space temperatures.

A.5.4 Variables

Variables included in the water heater model include the following:

- c_p = specific heat of water (assumed to be constant at 4810 kJ/kg-K)
- m_{draw} = mass of hot water drawn from the tankm_{tank} = mass of hot water contained in the tank
- Q_{del} = energy delivered by the water heater (in W)
- Q_{heat} = energy added to the tank by heaters (in W)
- Q_{loss} = standby energy loss (in W)
- t = time (in seconds)
- T_{amb} = ambient air temperature (in °F)
- $T_{deadband}$ = deadband temperature difference (in delta °F)
- T_{mains} = incoming mains water temperature (in °F)

- T_{set} = tank set point temperature (in °F)
- T_{tank} = average tank temperature (in °F)
- UA = tank overall heat loss coefficient (in W/K)
- $V_{draw,hot}$ = hot water draw volume from appliances (in gallons)
- $V_{draw,mixed}$ = mixed water draw volume from showers, sinks, and baths (in gallons)
- V_{tank} = tank storage volume (in gallons)
- η_{heat} = efficiency of the heating elements (always 1.0 for electric resistance water heaters)
- Ρ = density of water (assumed to be constant at 3.79 kg/gal).

A.5.5 Physical Equations

The fundamental equation governing the performance of the water heater is an energy balance on the tank. The energy balance is calculated as follows:

$$m_{tank} c_p \frac{dT}{dt} = Q_{loss} + Q_{del} + Q_{heat} \tag{A.1}$$

The individual heat flow terms are calculated as follows:

$$Q_{loss} = UA \cdot (T_{tank} - T_{amb}) \ . \tag{A.2}$$

$$Q_{del} = m_{draw} \cdot c_p \cdot t \ (T_{tank} - T_{mains}) \tag{A.3}$$

$$Q_{heat} = \ \eta_{heat} \cdot E_{cons} \tag{A.4}$$

At each time step, the heat removed from the tank due to tank losses and draws are calculated. If enough heat is removed for the tank temperature to fall below the water heater set point minus the deadband, the element will turn on. The element will stay on over multiple time steps until the set point temperature is achieved (and, if necessary, it will operate for part of the time step to avoid overshooting the set point). Specific controls and responses during a request for grid services are described below

A.5.6 End-Use Load

The end-use load considered here is the residential draw profile. The water heater model will always try to meet the load imposed on it by the draw profile, but after a large draw (especially at lower set point temperatures) it is possible for the tank to provide hot water below the useful set point of 110°F. In this case, all the mixed draw comes directly from the tank, but dissatisfaction with the temperature of hot water provided is not explicitly tracked anywhere in the model. Dissatisfaction with the temperature of the hot water provided could be calculated via linear interpolation of the beginning and ending tank temperatures at a given time step to estimate the fraction of the water delivered during that time step that is below the minimum allowable temperature (110°F)

A.5.7 Parasitic Loads

Parasitic loads are not currently considered for electric resistance water heaters because they are ~0.1% of operating power. The control module to enable grid response may consume a few watts of standby power, but the amount varies depending on the specific module and is not simulated here.

A.5.8 Possible Device Responses

If any grid services are requested, the water heater will determine if it has the capability to provide grid services. The control logic for providing grid services depends on the type of service requested. If there is a request to add load, the water heater will turn on as long as the water heater is below the maximum allowable temperature and exceeds the minimum required load-add capacity requirement. If there is a request to shed load, the water heater will turn off (if it would otherwise have been operating) as long as the water heater is above the minimum allowable temperature and exceeds the minimum required load-shed capacity. In the case where there is a request to shed load and the water heater would not otherwise have run, the water heater will stay off but it will not be counted as having provided a grid service, similarly for the load-add case if the water heater would have been operating even without the load-add request it will not be counted as having provided a grid service.

A.5.9 Constraints on Device Response

The main constraints on device response are listed above in terms of minimum and maximum temperatures and SoC. The only additional constraint is that there is a maximum number of times that the water heater can provide grid services. The maximum number of service calls that can be accepted is set by default to be 100, but this number can be reduced or increased if desired to model high-frequency services or to model people eventually choosing to opt out of providing grid services due to dissatisfaction with the water heating provided.

A.5.10 Device Model Validation

To validate the device model created here, EnergyPlus simulations were compared. EnergyPlus is DOE's flagship, state-of-the-art whole building energy simulation engine. The simulations were set up using a mixed tank in both EnergyPlus and the device model using identical inputs for mains water temperature, ambient air temperature, and the draw profile. Annual simulations were performed in both engines. There is a slight difference in how the draw profiles are handled in the different engines. In EnergyPlus, the tank performs iterations to figure out what mixed draw volume is required at the tank temperature during the time step, and the fraction of hot water required depends on the mains temperature (which varies daily) and the outlet temperature of that time step. In the Battery-Equivalent Model for this validation the mixed draw volume is assumed to be constant at 0.7. Depending on the exact conditions of a draw, the draw volume may be slightly higher or lower in the device model than in EnergyPlus. The annual average impact of this assumption is to increase the draw volume used by the device model, which leads to most of the discrepancy shown in Table A.1. For the particular day shown in Figure A.2 the EnergyPlus model draws slightly more water than the device model, leading to the longer recovery times for the EnergyPlus model. Even with this discrepancy, the temperature traces and timing of the heating element turning on are very similar and annual results are within 10%.

Table A.1. Annual comparison of the device model and EnergyPlus.

	Device Model	EnergyPlus	% Difference
Consumed Energy (kBtu)	12400	11700	-6.3%
Delivered Energy (kBtu)	11200	10500	-7.0%
Tank Losses (kBtu)	1160	1160	-0.1%
Draw Volume (gal/day)	68.7	63.2	-8.6%
Efficiency	0.907	0.900	-0.7%

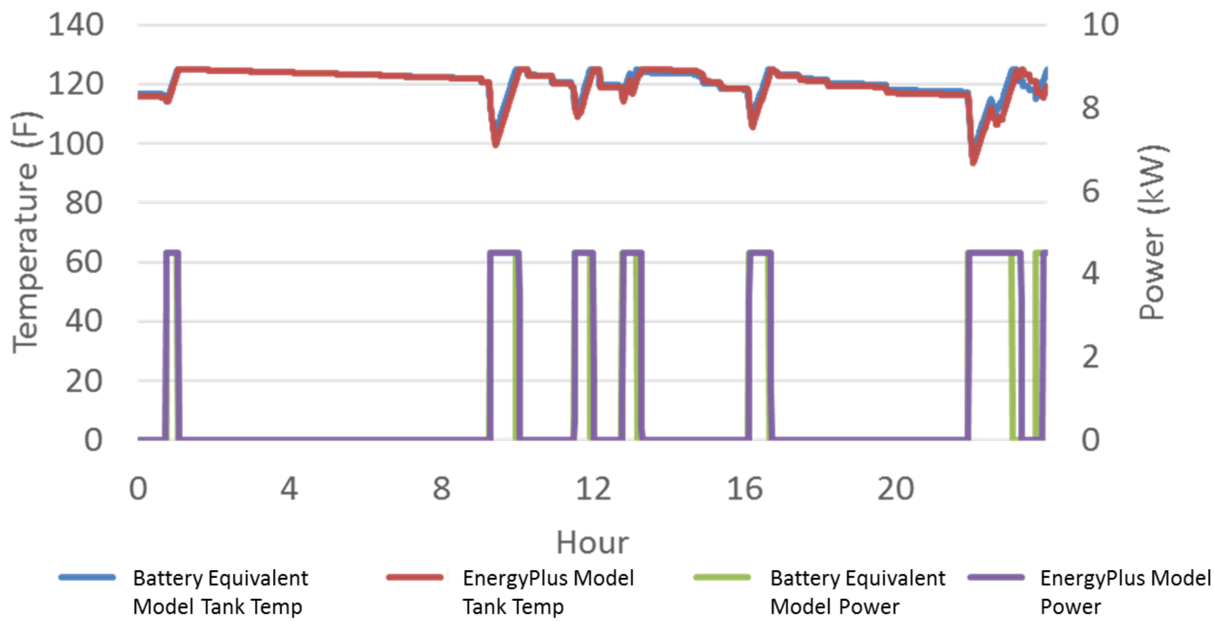

Figure A.2. Water heater tank temperatures and energy consumption in the device model and EnergyPlus.

A.5.11 Translating Device Model to Battery-Equivalent Model Parameters

A.5.12 Device Impact Metrics

A.5.12.1 Energy Impact and Metrics

No energy impact metrics are included here. The potential energy impacts of providing grid services depends on the service requested. However, the impact of adding load and overheating the tank are likely to be larger than those of shedding load, and units providing grid services are likely to have a higher overall energy consumption. When load is added, the tank heats up when it otherwise would not. Along with the additional energy consumption, the higher tank temperatures lead to higher losses to the environment. In the case of a load-shed event, the tank losses are slightly reduced, but the tank will still need to come back to the set point temperature after the shed event has ended.

A.5.12.2 Amenity Impacts Metrics

The only possible amenity metric for this model would be an unmet hot water load. Unmet hot water loads are not tracked here for two main reasons. First, some unmet hot water loads may not be noticed by the occupant (for example, a dishwasher draw). Additionally, the water heater would likely run out of hot water during certain high-use scenarios (such as several showers in a row) even if grid services were not being provided, which makes it difficult to determine if the cause of an unmet load was due to user behavior or the grid services provided.

A.5.12.3 Equipment Impacts Metrics

None

A.6 Device Fleet

A.6.1 Default Fleet Characteristics (Instantiation)

Default fleet characteristics include the following:

- The number of water heaters that are explicitly modeled. The default is 10.
- The size of the fleet represented – The actual number of water heaters that are represented by the ones that were explicitly modeled. It is assumed that each water heater that is modeled is representative of a larger number of identical water heaters. This sort of scaling greatly reduces the run time of the model while still reasonably representing a large fleet of water heaters. The default is 10,000. The distribution of tank sizes is shown in Table A.2.

Table A.2. Distribution of Tank Sizes

Tank Size (gal)	Distribution (%)
40	20
50	70
80	10

- Initial tank set point temperature – The initial tank temperature is set using a normal distribution with a mean of 123°F and a standard deviation of 9.7°F. Values were chosen based on a nationally representative sample of actual water heater performance in the field. There is a lower limit on this distribution of 110°F (anything below this would get set to 110°F).
- Initial tank temperature – The initial tank temperature is set using the same probability distribution as the set point temperature, but with a limit that the starting tank temperature cannot be higher than the set point temperature.
- Installation location of the water heater – 67% of the water heaters are installed in unconditioned space and 33% are installed in conditioned space. For homes in Denver, the unconditioned space is an unfinished basement, but in other climates other unconditioned spaces could be used as the installation location instead (for example, garage installations are common in warmer climates).
- Maximum number of annual service calls – The number of service calls that can be accepted in a year. This can be used to simulate how often people are willing to accept

service calls that could potentially impact their available hot water. The default value is 100 for all water heaters, but this variable is set up to be able to handle a probability distribution to capture different occupant preferences.

A.6.2 Coordination Scheme

Once the availability of all water heaters in the fleet has been determined, the total grid service request is divided equally among each available water heater and they each provide their service. Note that during the time step, if a given water heater is providing a service and it reaches a limitation (either high or low SoC) it will cease to perform the service and will maintain operation at the limiting SoC. The number of water heaters experiencing this condition is minimized by requiring a minimum available capacity (in addition to SoC because water heaters are of different storage capacities) to participate in the grid service. However, this is not a guarantee of availability because the water heaters might experience a large draw during the service. This means that it is possible that the total service amount requested of the fleet might not be met at a given time step even if there appears to be sufficient capacity to do so.

A.6.3 Example Usage

To demonstrate the usage of this model, an example fleet in Denver, Colorado, was simulated. This average fleet consisted of 10 unique water heater models, each intended to represent 100 actual water heaters. This fleet was subjected to an example daily request for load-add and shed based on current time-of-use (TOU) pricing structures available. Each day, during the summer a TOU period with higher pricing occurred between 7a.m.and 5 p.m. To try to shift load outside of this period, each water heater was given a command to add load as much as possible in the period prior to the higher pricing period and then shed load during the entire period. As shown in Figure A.3, the water heaters showed normal operation (with one to four of the water heaters on at any given time) during times when no service was requested. During periods when services were requested, the requested service was large enough that all of the water heaters turned on and tried to fully charge. They were able to sufficiently charge in the 3 hours prior to the event so that none of the units needed to draw power during the higher rate period, and on many days they were still charged enough to coast for a short time after the event. In some cases (such as the last day), there were larger than usual hot water draws during the load-shed period, which led to more units than usual turning on post event.

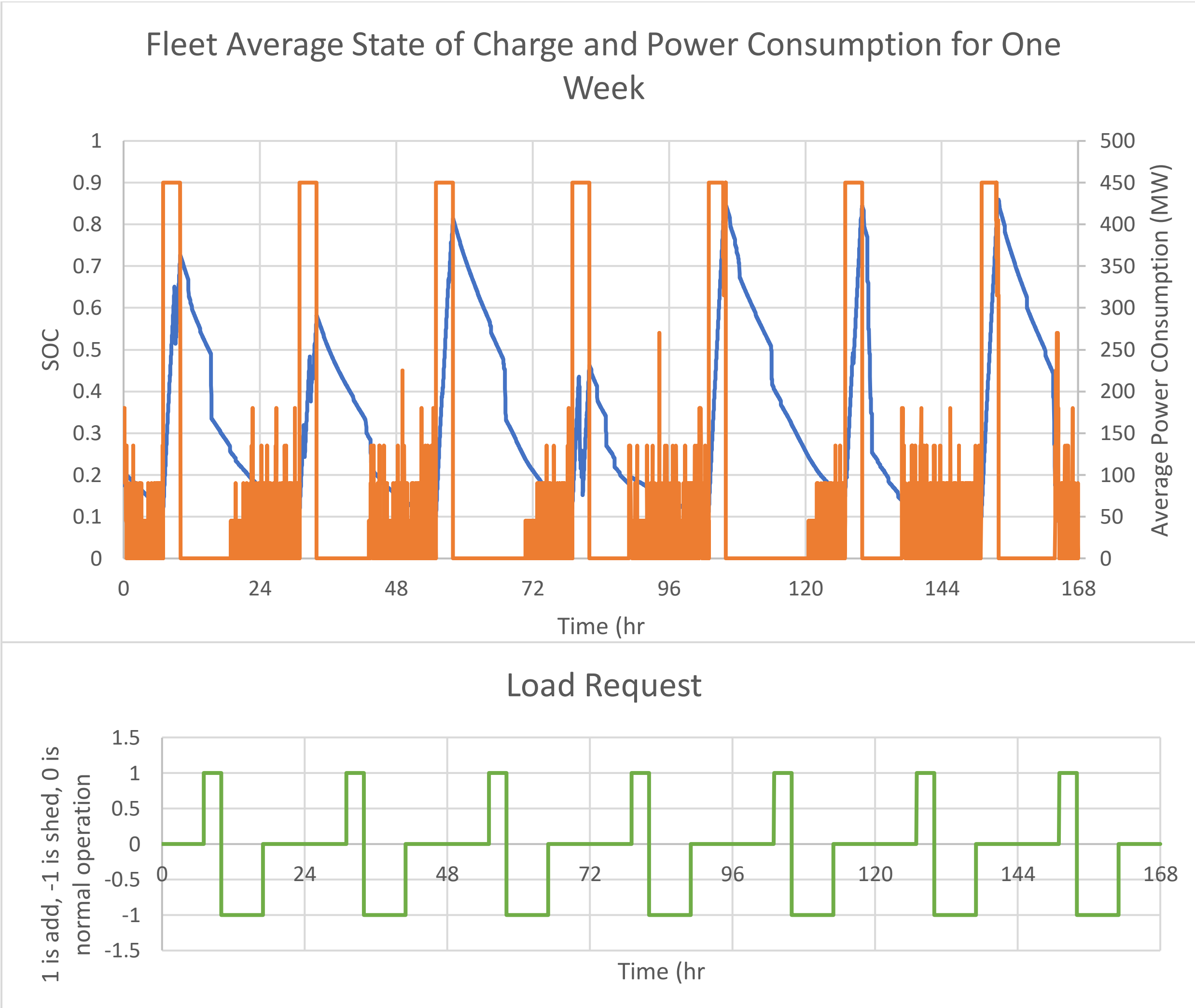

Figure A.3. Fleet average state of charge and power consumption for one week and the load request.

Appendix B – Electric Vehicles

B.1 Basic Device Purpose

An electric vehicle (EV) is defined as a vehicle that uses energy stored in rechargeable batteries for drivetrain power and is plugged into the grid to recharge. Although there are multiple types of vehicles that use electric energy to power their powertrains, the focus of this device model are battery-electric vehicles (BEVs)(plug-in hybrid electric vehicles [PHEVs], which have more complex driving patterns, are omitted). The purpose of the EVs (at the current state of the art) is to provide an alternative transportation method to conventional and hybrid vehicles.

B.2 Standard Controls and Normal Operational Modes

Due to the current state of the art of EVs, this device model only considers unidirectional charging. That is, Vehicle-To-Grid (V2G) communication to vary charging rate or provide battery power from the device to the grid is not enabled. Therefore, the normal operational modes are assumed to be as follows:

- Driving – The EV is discharged during driving and power from the grid is not consumed.
- Charging at work and other non-residential locations – Some EVs in the fleet are charged at work and other locations. Grid power is demanded by the battery of the EV, but this power is assumed to be uncontrollable.
- Charging at home:
  - Charging mode 1 – EVs start charging immediately after arriving home.
  - Charging mode 2 – EVs start charging at a predefined time, usually midnight. This charging mode is often included in the software of the EVs that is developed by the Original Equipment Manufacturers (OEMs).
  - Charging mode 3 – EVs start charging as late as possible with the aim to be fully charged before the "Time Charge is Needed" (TCIN). This is an example of a smart charging mode that most OEMs include in their software for EVs.

Being consistent with the actual state of the art of EVs, the controls are quite simple. The controls considered in this model are **turn off/on chargers of vehicles that are plugged in at home and have selected Charging Mode 1**. EVs that are being charged with Charging Mode 2, only have 5–6 hours of plug-in availability at home and thus, some vehicles must be careful not to run out of time before in order to be fully charged by the next day. By definition, Charging Mode 3 cannot be controlled because V2G communication is assumed to be disabled. Furthermore, all the EVs are assumed to be charged at the maximum power of the installation; i.e., AC power cannot be regulated to track the request.

B.3 Equipment Availability and Usage Patterns

The availability of an EV is mostly reduced to the time when the vehicle is plugged in at home, however a small fraction of vehicles are modeled to be plugged in at work. Charging can be turned on/off depending on the power request from a particular grid service. Usually, the availability of this device occurs after returning home from work around 5–6 p.m. until the next day between 7–8 a.m. when cars are used to commute to work.

Based on National Household Travel Survey (NHTS) 2009 survey data (NHTS 2009), the daily schedules of cars are gathered and shown in this section. First, histograms of the time of leaving home and the time of arriving home for only passenger cars are shown in Figure B.1. Figure B.1 shows some differences between weekday and weekend schedules. While on the weekdays, there are big peaks at the time the cars leave home to go to work and the cars arrive home after work, on the weekends the distributions are flatter.

The availability of passenger cars, that is, time when they are parked at home, is shown in Figure B.2. As can be observed, on weekdays, the histogram of the average time parked at home tends to follow a bi-normal distribution with peaks around 14 and 22 hours a day. However, on weekends, the mode is around 23 hours because many cars are parked the entire day.

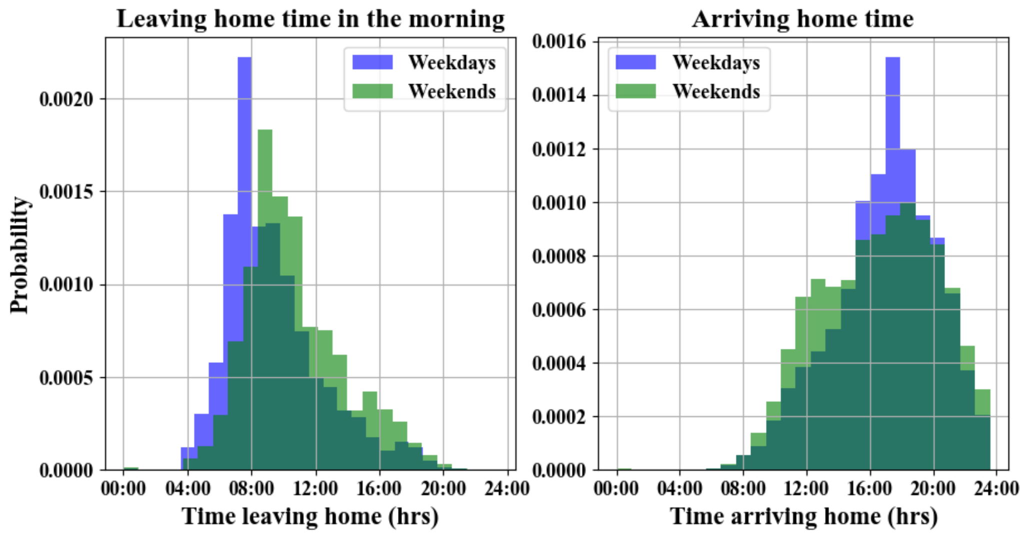

Figure B.1. Histograms of the time "leaving home" (left) and time "arriving home" (right) for weekdays (blue) and weekends (green) from the 2009 NHTS survey data.

Finally, the percentage of cars parked at home as a function of time of the day is shown in Figure B.3. In this case, for both weekdays and weekends, the smallest percentage of cars parked at home appears to occur around 12 p.m., when the majority of the vehicles are parked at work or other locations, but not at home. Therefore, around noon, there is likely to be the lowest population of plugged-in EVs to provide grid services. In this model, EVs plugged in at home are the only ones that are able to provide grid services.

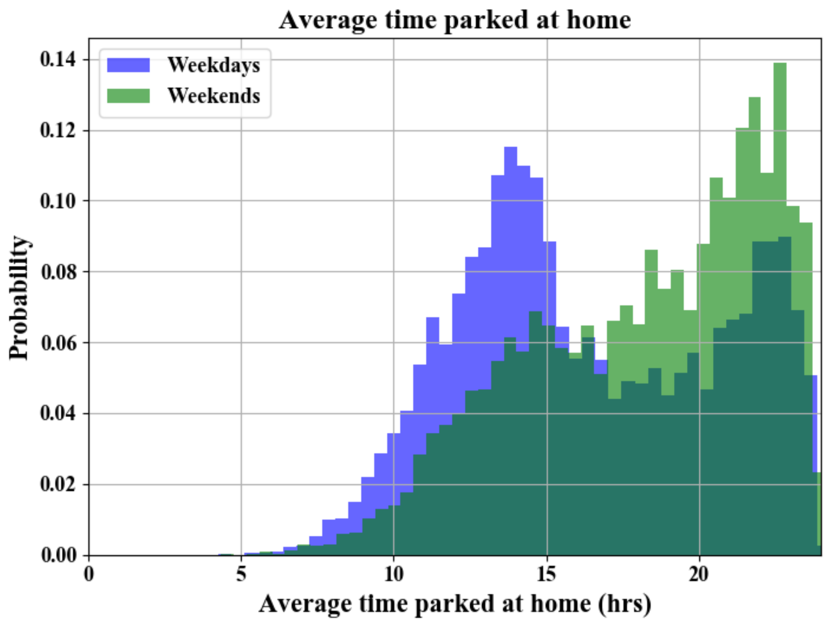

Figure B.2. Histograms of the average time parked at home on weekdays (blue) and on weekends (green) from the 2009 NHTS survey data.

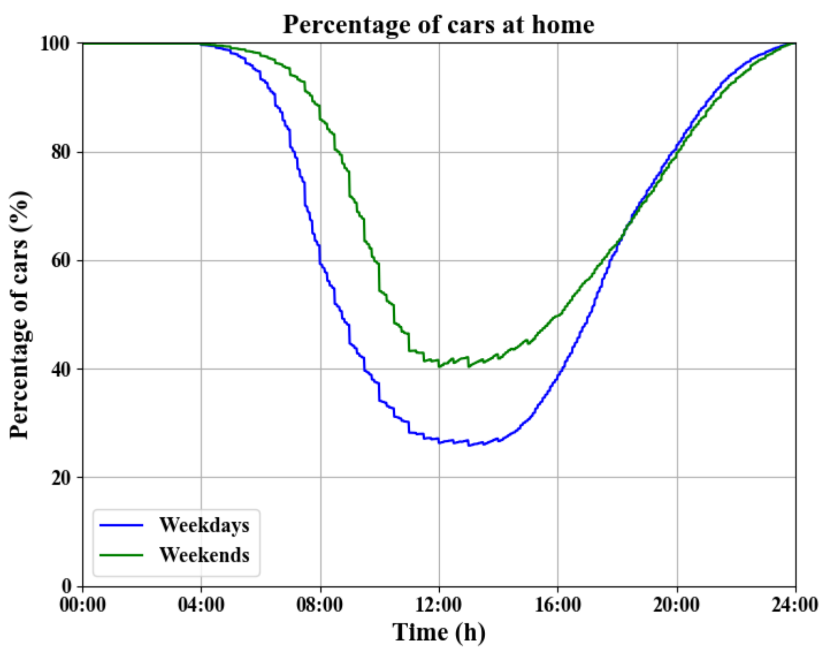

Figure B.3. Percentage of cars at home as a function of time on weekdays (blue) and on weekends (green) from the 2009 NHTS survey data.

Although the above figures show differences between weekends and weekdays in terms of the availability of electric cars, both are weighted together in this model to provide a combined data set of driving patterns and availability of EVs. In this manner, the process of matching the daily schedule of the devices with the data is simplified as explained in this appendix.

B.4 Change in Power Output Resulting from Response

The charger of an EV without V2G communications or smart charging devices like the ones considered in this model cannot regulate the power consumed. Therefore, an EV responds to a request by having information about the rest of the fleet and the request itself in this way, as follows:

1. If the power requested is positive (power greater than the baseline case), an EV will stop charging if it is required to meet the request. The number of cars that stop charging depends on the amount of power requested. This change in power output is constrained by the TCIN of the next day; i.e., if an EV must start charging to be fully charged before the TCIN of the next day, it will charge and positive service requests will not be met.
2. If the power requested is negative (power less than the baseline case), an EV will start charging if it is required to meet the request. The number of cars that start charging depends on the amount of power requested. This change in power output is constrained by the state of charge (SoC) of the vehicle; i.e., when the battery of the EV is fully charged, negative service requests will not be met.

B.5 Device Model

B.5.1 Assumptions

The model developed for EVs is based on the following assumptions:

- To model the entire fleet of electric cars, a **mesoscopic model** is considered. That is, homogeneous groups of EVs with the same parameters and equipment characteristics are grouped into sub-fleets as shown in Figure B.4. This way, the model is easily scalable and computationally efficient regardless of the number of EVs.
- Bidirectional charging is not allowed.
- DC fast-charging stations and vehicles charging en route during very long trips are not considered in this model.
- Only pure BEVs are included in this model and PHEVs are omitted.
- Because a pure resistive battery model is considered for this device, responses to reactive power requests cannot be met. Only active power requests can be met.
- Although some differences in the availability of EVs are observed depending on the day of the week, the driving schedule is assumed to be independent of the day of the week to simplify the process of matching the schedules.
- The daily mileage of an EV driving schedule follows a Weibull distribution with a mode of one-third the range of the EV (Tal et al. 2014). Therefore, the process of matching the vehicle driving schedule to the NHTS data is as follows:
  - Calculate the range of the EV based on the capacity of its battery and the SoC at the beginning of the day. (As a boundary condition, EVs are assumed to be fully charged at the beginning of the day.)
  - Based on the calculated range, generate a random number that follows the Weibull distribution with the mode of one-third the range of the vehicle (Figure B.5) to obtain the miles driven on a particular day.

- Match the driving schedule with the NHTS data of driving patterns for cars by using the miles driven on this particular day. That is, by using the daily miles driven calculated in the previous step, the driving schedule from NHTS data with the closest daily to the calculated daily miles is found. This driving schedule with the same daily distance is assumed to be the driving schedule of the sub-fleet.

- Only devices that are charged with the Charging Mode 1 can be turned on/off depending on the request to control the power output of the entire fleet.

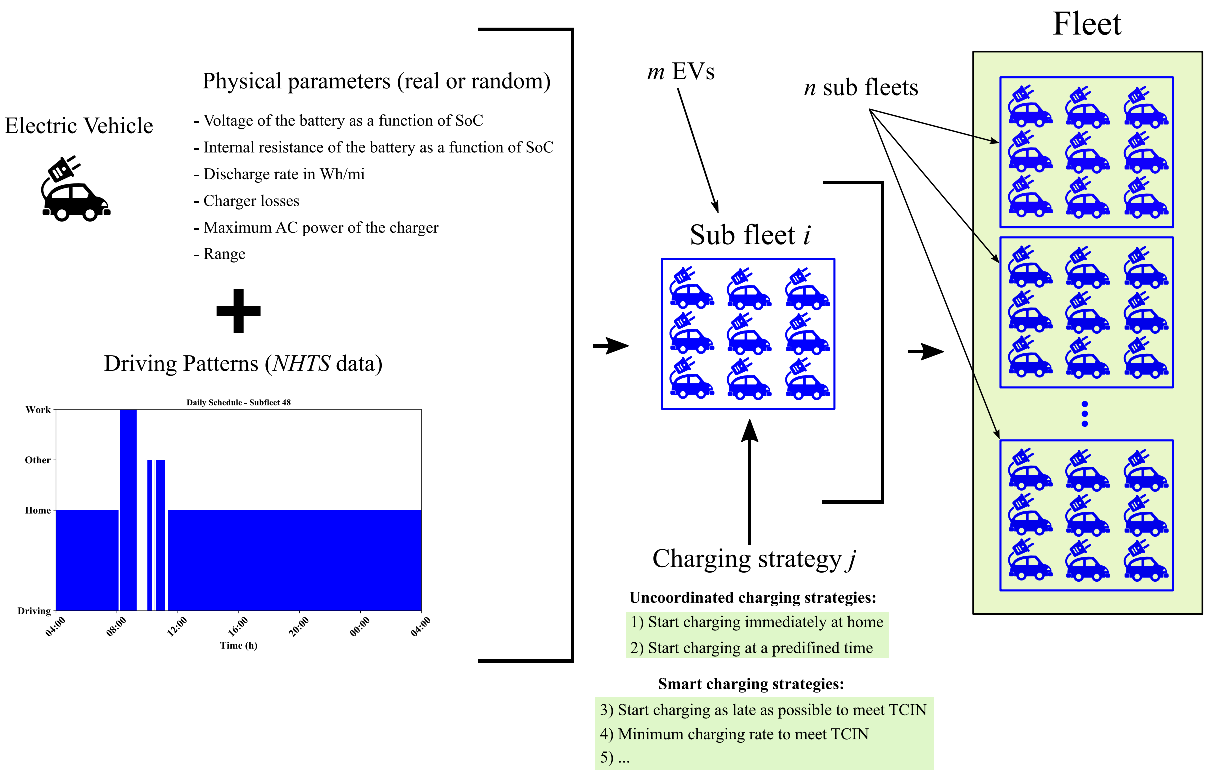

Figure B.4. Schematic of the mesoscopic model considered in this model. The physical parameters are taken from the electric vehicle model and along with the daily schedule, the sub-fleet is created, which is the minimum component of the model. Then, each sub-fleet is associated with a charging strategy to populate the fleet of EVs.

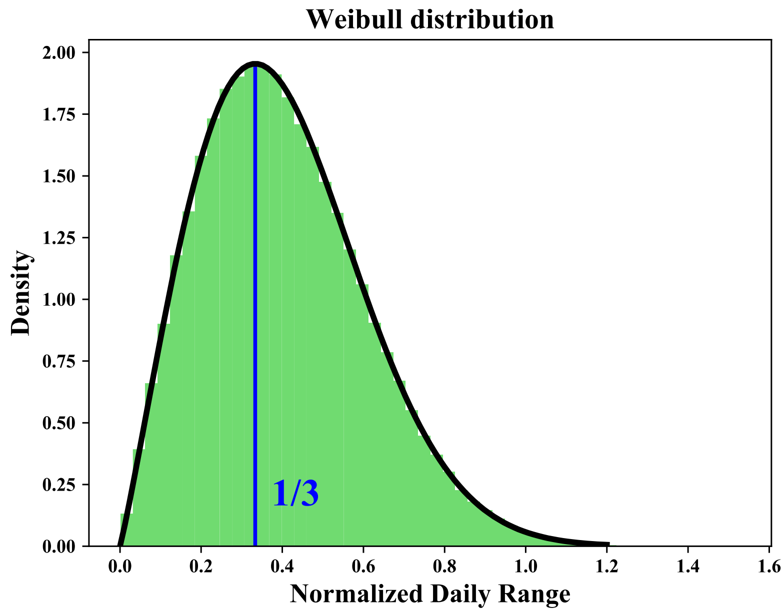

Figure B.5. Weibull distribution with mode at one-third the range of the electric vehicle.

B.5.2 Parameters/Equipment Characteristics

The equipment characteristics are the rate of discharge per mile, the number of cells of the battery, the coefficients to calculate the open circuit voltage of the battery as a function of the SoC, the coefficients to calculate the internal resistance of the battery as a function of the SoC, the electrical losses of the charger due to the transformation of AC to DC power, and the capacity of the battery.

B.5.3 Boundary Conditions

The boundary conditions considered in this model are as follows:

- The minimum and maximum SoC of the battery of BEV are assumed to be 0 and 100%, respectively.
- All the BEVs must be fully charged at least 1 hour before the TCIN.
- The location of the charger of the EV that determines the AC power, voltage, and frequency oscillations. For example, charging the vehicle at home use will provide a voltage of 240 V, while charging the car at work or other places will provide a voltage of 208 V.

B.5.4 Variables

The variables that depend on the time are the SoC of the EV battery, the voltage of the battery, the internal resistance of the battery, the current draw, and the power to grid while charging.

B.5.5 Physical Equations

The fundamental equations governing EVs model are presented below.

- The open-circuit voltage of the battery is calculated as follows:

$$V_{OC}(SoC) = (V_0 + V_1 \cdot SoC + V_2 \cdot SoC^2) \cdot N_{\text{cells}} \tag{B.1}$$

Coefficients V_0, V_1, and V_2 of each vehicle considered in this model are obtained by least-square fitting of experimental results. The number of unit cells in the battery is represented by N_{cells}.

- The internal resistance of the battery as a function of the SoC is calculated as follows:

$$R_{\text{batt}}(SoC) = R_0 + R_1 \cdot SoC + R_2 \cdot SoC^2 \tag{B.2}$$

Coefficients R_0, R_1, and R_2 of each vehicle considered in this model are obtained by least-square fitting of experimental results.

- The DC power of the charger as a function of the AC power is calculated as follows:

$$P_{DC} = P_{AC} - (AC_{L0} + AC_{L1} \cdot P_{AC} + AC_{L2} \cdot P_{AC}^2) \tag{B.3}$$

From vehicle testing, DC-AC power losses are modeled as a second-order polynomial in terms of the AC power from the charger. This way, the DC power that charges the battery can be expressed in terms of the AC power. The coefficients AC_{L0}, AC_{L1}, and AC_{L2} of each vehicle considered in this model are obtained by least-square fitting of experimental results.

- The current of the battery is calculated as follows:

$$I_{\text{batt}} = \frac{V_{OC} - \sqrt{V_{OC}^2 - 4R_{\text{batt}}P_{DC}}}{2R_{\text{batt}}} \tag{B.4}$$

- The range of the EV is calculated as follows:

$$\text{Range} = \frac{\text{SoC} \cdot Ah_{\text{nom}} \cdot V(SoC)}{E_c} \tag{B.5}$$

  where E_c is the average energy consumption measured in watt-hours per mile.

- The discharge of the battery while driving is calculated as follows:

$$SoC_i(t) = SoC_i(t_0) - \frac{\left(\frac{Wh}{mi}\right)_i}{V_i \cdot (Ah_{\text{nom}})_i} \cdot \left(\frac{\Delta mi}{\Delta t}\right)_i^j \cdot (t - t_0) = SoC_i(t_0) - \dot{SoC}_{i\ dis}^{j}(t - t_0) \tag{B.6}$$

where:

$SoC_i(t)$	=	state of charge of the sub-fleet i at time $t = t_0 + \Delta t$,
$SoC_i(t_0)$	=	state of charge of the sub-fleet i at time t_0,
$\left(\frac{Wh}{mi}\right)_i$	=	rate of discharge of the sub-fleet i,
V_i	=	voltage of the battery while discharging of the sub-fleet i,
$(Ah_{nom})_i$	=	capacity of the battery of the sub-fleet i,
$\left(\frac{\Delta mi}{\Delta t}\right)_i^j$	=	average speed of the trip j of the sub-fleet i calculated dividing the miles driven in the trip by the duration of the trip from NHTS data,

$\dot{SoC}_{i\ dis}^{j}$ = rate of change of SoC of the fleet i at trip j while discharging, and
t = time expressed in seconds.

- The charge of the battery at home is calculated as follows:

$$SoC_i(t) = SoC_i(t_0) + \frac{I_{\mathrm{batt}_i}}{3600 \cdot \mathrm{Ah}_{\mathrm{nom}_i}} = SoC_i(t_0) + \dot{SoC}_{i_{char}} \cdot (t - t_0) \qquad \text{(B.7)}$$

where $\dot{SoC}_{i_{char}}$ is the rate of change of SoC of the fleet i while charging.

- The time to start charging for Charging Mode 3 is calculated as follows:

$$t_{init} = (t_{tcin} - t_{gap}) - \frac{1 - SoC_i(t_{init})}{\dot{SoC}_{i_{char}}} \qquad \text{(B.8)}$$

where t_{gap} is the time before the TCIN at which the sub-fleet must be fully charged. In this model, we consider $t_{gap} = 3600$ sec.

B.5.6 End-Use Load (if any)

The only end-use load that is considered in the model of BEVs is the necessity of charging the sub-fleets when they are parked at home to meet the boundary condition of being fully charged at least 1 hour before the TCIN. As stated in the Physical Equations section, charging losses (AC-DC) are considered and are part of the end-use load.

B.5.7 Parasitic Loads (if any)

None

B.5.8 Possible Device Responses

The only device response considered in this model is to curtail/start charging (charging is always at the maximum AC power of the charger) for a portion of the devices that are being charged using the Charging Mode 1 depending on the service request. The power demanded from the grid by the devices that are charged using Charging Mode 2 and Charging Mode 3 is supposed to be uncontrollable regardless of the service request.

B.5.9 Autonomous Operation

Autonomous responses to local grid conditions is configured to match the 2018 Institute of Electrical and Electronics Engineers (IEEE) 1547 Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces (IEEE 2018). The frequency/power function is implemented using the following two equations.

- Operation for low-frequency conditions:

$$p = \min_{f < 60 - db_{\mathrm{UF}}} \left\{ p_{\mathrm{pre}} + \frac{(60 - db_{\mathrm{UF}}) - f}{60 k_{\mathrm{UF}}} ; p_{\mathrm{avl}} \right\} \qquad \text{(B.9)}$$

- Operation for high-frequency conditions:

$$p = \min_{f>60+db_{\mathrm{OF}}} \{p_{\mathrm{pre}} + f - \frac{(60-db_{\mathrm{OF}})}{60k_{\mathrm{OF}}}; p_{\mathrm{min}}\} \tag{B.10}$$

where

p	=	the active power output,104 in p.u. of the distributed energy resource (DER) nameplate active power rating;
f	=	the disturbed system frequency in hertz (Hz);
p_{avl}	=	the available active power, in p.u. of the DER rating;
p_{pre}	=	the pre-disturbance active power output, defined by the active power output at the point of time the frequency exceeds the deadband, in p.u. of the DER rating;
p_{min}	=	the minimum active power output due to DER prime mover constraints, in p.u. of the DER rating;
db_{OF}	=	a single-sided deadband value for high-frequency, in Hz;
db_{UF}	=	a single-sided deadband value for low-frequency, in Hz;
k_{OF}	=	the per-unit frequency change corresponding to 1 per-unit power output change (frequency droop), unitless; and
k_{UF}	=	the per-unit frequency change corresponding to 1 per-unit power output change (frequency droop), unitless.

Note that the SoC of each sub-fleet is modified according to the change in power due to the autonomous operation response. The modified SoC results in the following equation:

$$SoC_{aut}(t+1) = SoC(t) + \frac{p_{aut}}{p_{norm}}[SoC_{norm}(t+1) - SoC(t)] \tag{B.11}$$

where

$SoC(t)$	=	the SoC of the sub-fleet at the beginning of the grid request;
$SoC_{norm}(t+1)$	=	the SoC of the sub-fleet at the end of the grid request without considering autonomous response;
$SoC_{aut}(t+1)$	=	the SoC of the sub-fleet at the end of the grid service request considering autonomous response; and
p_{aut} and p_{norm}	=	the active powers to the grid of each sub-fleet considering and without considering autonomous response, respectively.

Autonomous operation to respond to nominal voltage deviation is not considered in this model because reactive power is assumed to be zero.

B.5.10 Constraints on Device Response

The only constraint considered in this model is that <u>all sub-fleets must be fully charged at least 1 hour before the TCIN</u>. At each timestamp when any service is requested, the model calculates the time to start charging by using the following equation:

$$t_{init} = (t_{tcin} - t_{gap}) - \frac{1 - SoC_i(t_{init})}{\dot{SoC}_{i_{char}}} \tag{B.12}$$

If the time is before t_{init}, the device accepts curtailment or starting of charge depending on the service request, while for times greater than t_{init}, the power cannot be controlled and the device will be charging until being fully charged before the TCIN.

B.5.11 Device Impact Metrics

Inability to meet a constraint unless the constraint is on the device response is actively included in the model.

B.5.11.1 Energy Impact Metrics

None

B.5.11.2 Amenity Impacts Metrics

Although amenity impact metrics are not calculated in this model, in some situations in real life, the constraint of being fully charged before TCIN might not be always met. Therefore, an amenity impact that might be included in real-life scenarios is the “driver’s anxiety” about having only a partial charge of the battery for commuting to work the next day.

B.5.11.3 Equipment Impacts Metrics

None

B.6 Device Fleet

B.6.1 Default Fleet Characteristics (Instantiation)

Instantiation of the fleet is required to respond to requests in the form of grid service power. To instantiate the fleet, baseline power of the fleet and baseline SoC of the sub-fleets are required.

To obtain the baseline power and SoC from which the Battery-Equivalent Model can be referenced, the different charging strategies must be combined. The percentage of cars that implement each charging strategy is a parameter that must be assumed to model the baseline power and the SoC. The equations used are as follows:

$$P_{base} = \sum_{i=1}^{3} w_i P_i \qquad \text{(B.13)}$$

$$SoC_{base} = \sum_{i=1}^{3} w_i SoC_i \qquad \text{(B.14)}$$

where w_i is the percentage of vehicles charging using the charging strategy i.

To generate baseline power and initialize the SoC of the sub-fleets while avoiding random variability, Montecarlo simulations with different random seeds are required. Note that each time the user of the API changes the parameters of this model, new Montecarlo simulations are required to provide the correct baseline.

In Figure B.6, a simulation of seven days with 100 sub-fleets of 200,000 BEVs is shown as an example. The baseline power and SoC of the fleet as a function of time is shown for all three charging modes. Baseline power and SoC are then aggregated with their corresponding weights (percentage of sub-fleets that use each charging strategy). Figure B.7 shows the weighted baseline power and SoC with the following weights: 40% of sub-fleets are being charged using the Charging mode 1, 30% using Charging mode 2, and 30% using Charging mode 3. Because all the sub-fleets were initialized with 100 % of SoC at the beginning of the simulation (4:00 a.m.), the first day is called a “burn-in” day and it is ommited from the final baseline power and SoC.

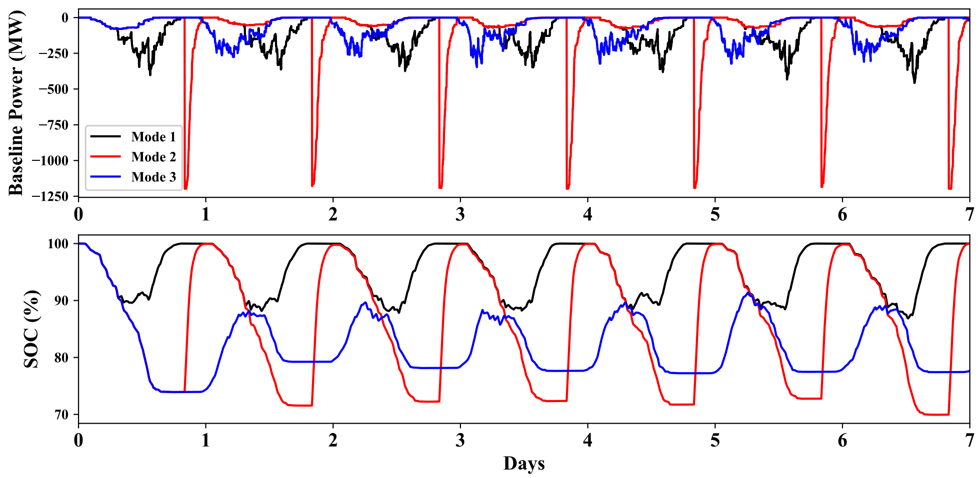

Figure B.6. Baseline power demanded to the grid and SoC of a fleet of 200,000 BEVs as functions of time.

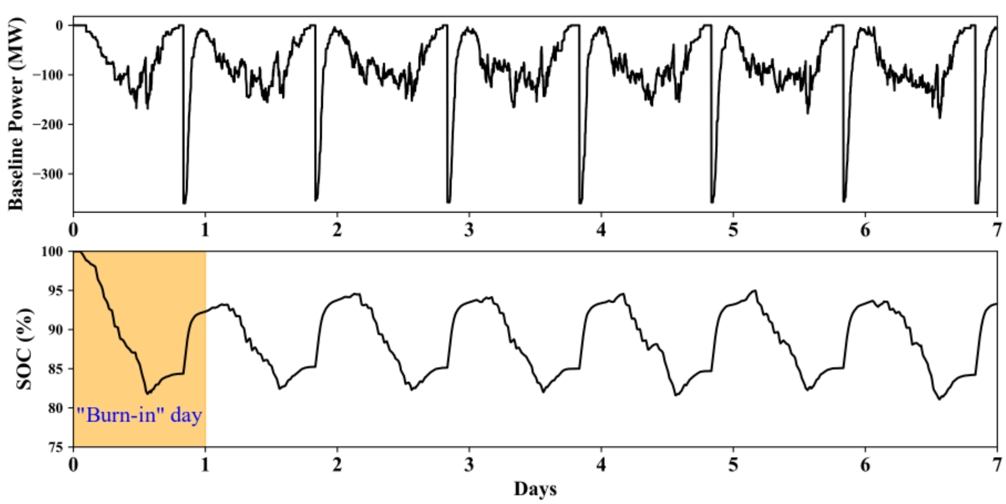

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Figure B.7. Aggregated baseline power to the grid and SoC of a fleet of 200,000 BEVs as functions of time. Weights are: $\boldsymbol{w_1} = \mathbf{0.4}$, $\boldsymbol{w_2} = \mathbf{0.3}$, and $\boldsymbol{w_3} = \mathbf{0.3}$.

The randomness of the daily schedules and charging events requires Montecarlo simulations to initialize both the power and the SoC of the Battery-Equivalent Model of the electric cars in the fleet. At least a 10-day Montecarlo simulation is required to provide an accurate representation of the baseline case. Also, **each time the parameters of the model are changed, a new baseline simulation must be run.**

Therefore, the baseline power will be the average power from Montecarlo simulations, while the initialization of the SoC of the sub-fleets is solved by taking the following two steps:

1. Run Montecarlo simulations for each charging strategy and store the average SoC of the fleet and the standard deviation, which represents the variability within different sub-fleets.
2. With the average SoC and the standard deviation for each charging mode, generate random numbers that follow a truncated normal distribution between 0 and 100% of SoC for each sub-fleet.

As an example, the average SoC and standard deviation from a 10-day Montecarlo simulation is shown in Figure B.8.

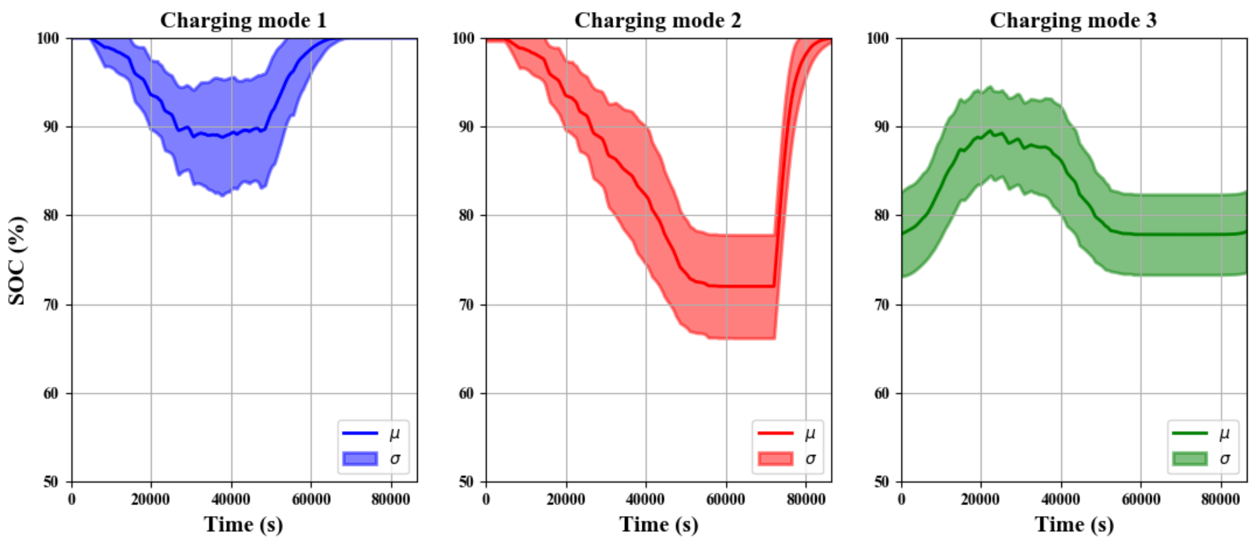

Figure B.8. The state of charge of the fleet and standard deviation as a function of time for the three charging modes considered in the model. Note that $t = 0$ sec corresponds to 4 a.m.

B.6.2 Coordination Scheme

Once the baseline power has been calculated, the coordination scheme to meet the requests is implemented. In this model, a very simple coordination scheme has been used: sub-fleets that are charged using the Charging Mode 1 will turn on/off their chargers to meet the request. The coordination scheme gives priority to the least charged sub-fleets to turn on their chargers. As explained above, the coordination scheme is constrained by the TCIN. That is, all the sub-fleets must be fully charged at least 1 hour before the TCIN.

Note that the sub-fleets that are being charged using Charging Mode 2 and Charging Mode 3 do not have the capability to change their power output depending on the service request.

B.6.3 Example Usage

Simulation results for a fleet of 200,000 BEVs with 100 sub-fleets (2,000 BEVs per sub-fleet) are presented in this section. This example considers that 40% of sub-fleets are charged using Charging Mode 1, 30% using Charging Mode 2, and 30% using Charging Mode 3.

A 24-hours “dummy” grid service is run to test the efficacy of this fleet to respond to grid services. In this case, the grid service request implemented is assumed to be:

$$P_{\mathrm{req}}(t) = P_0 \left[1 + \sin\left(\frac{2\pi t}{T}\right)\right] \tag{B.15}$$

The response to this request is shown in Figure B.9. As can be observed, at the beginning of the day, when most vehicles are driving or being charged at work or other places, the availability is the lowest and, thus, the fleet is not able to accurately track the grid service request. On the other hand, when the availability starts to increase at around 4 p.m., the fleet is progressively able to meet the request. At the highest availability (5 p.m.–1 a.m.), the fleet perfectly tracks the grid service request. Note that both the power request and service are referenced to the baseline power calculated from the Montecarlo simulations.

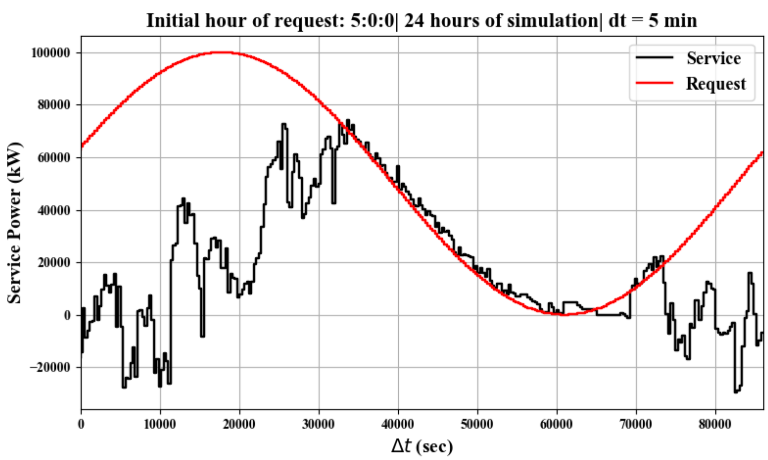

Figure B.9. Response to a 24-hour dummy grid service request. The red line represents the request as a function of time and the black line represents the service power provided by the fleet.

B.7 References

IEEE (Institute of Electrical and Electronics Engineers) 2018. Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003), pp 1–138. Piscataway, New Jersey.

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Appendix C – Photovoltaic System

C.1 Basic Device Purpose

The basic purpose of a photovoltaic (PV) solar/inverter system (also termed as “PV system” in this section) is to convert solar energy into usable electrical energy. In doing so, the solar module first converts the solar energy into electrical direct current (DC) power that is then converted into electrical alternating current (AC) power by the inverter. Because the conversion is primarily driven by solar irradiance, the available electrical power from the photovoltaic solar/inverter system is a strong function of seasonal and diurnal solar energy intensity and of temperature. The maximum power point tracking (MPPT) algorithm plays a crucial role in extracting energy from PV modules. Maximum power varies strongly with the seasonal and hourly patterns of sun angles and the sky clearness index. In addition to the real power, PV inverters can provide reactive power autonomously or by following a set point. The maximum reactive power availability depends on the kilovolt-ampere(s) reactive (kvar) rating of the inverter.

C.2 Standard Controls and Normal Operational Modes

Photovoltaic solar/inverter systems with advanced grid functions can operate in different modes to provide a variety of grid services. The modes and characterizing parameters of the PV system can be set locally or by remote control signals coming from any authorized entity through a proper communication channel. Standard controls and normal operational modes of PV systems fall under real power delivery, ride-through capability, active power modes (watt modes), and reactive power capability (var capability) and modes, as summarized below.

- Real power delivery
  - MPPT (Autonomous – Typical):

    The available solar power from a PV system varies from time to time due to variation in solar irradiance and temperature. MPPT techniques are used in the inverter controls to extract maximum power from the PV system at any time. Grid-connected PV systems typically run a MPPT algorithm to maximize energy injection from the PV to grid.
  - Constant power control (CPC):

    In CPC mode, the PV system generates constant real power following a local or remote control signal as long as the reference power is below the maximum available power from the PV at that time instant. When no energy storage is used, power management of aggregated PV systems or modification of MPPT algorithms can be two ways to achieve CPC control.
- Ride-through capability

  With high penetration of PV into the electric grid, PV systems have to stay connected to the power network providing grid support during disturbances corresponding to certain faults, because disconnection of PV systems may further degrade the power system operation. The ride-through capability determines the ability of the PV system to remain connected to grid under abnormal grid conditions.

– Voltage ride through (VRT)

  Many grid codes and standards, e.g., IEEE 1547, require that a PV system has to ride through any voltage fluctuation within an allowable range (voltage deadband), thereby maintaining synchronism with the power system. Outside of the voltage deadband, the PV systems may disconnect from the grid if the voltage disturbance continues longer than the trip time specified by the grid code. Grid codes and standards specify the range of voltage deadband, ride-through times for different level of voltage disturbances, and trip times.

– Frequency ride through (FRT)

  Similar to VRT, a PV system has to ride through any frequency fluctuation within an allowable range (frequency deadband), thereby maintaining synchronism with the power system. Outside of the frequency deadband, the PV systems will stay connected with the grid for at least a period of time (ride-through time) following a frequency disturbance and the ride-through time depends on the level of frequency disturbance. The PV systems may disconnect from the grid if the frequency disturbance continues longer than the respective trip time. Grid codes and standards specify the range of frequency deadband, ride-through times for different level of frequency disturbances, and trip times.

- Watt modes (Revised IEEE 1547 or IEEE P1547)

  The watt modes of PV systems for grid services focus on different ways of delivering real power to the grid from the PV depending on various remote and local signals and grid conditions. Existing standards, e.g., IEEE P1547, can be followed for the response time and ramp rate for real power change under different watt modes.

  – Curtailment

    Under this mode, the PV generates reduced power compared to the power corresponding to the maximum power point (MPP). Curtailment is similar to the CPC mode of operation.

  – Frequency-watt response (Typically down regulation; up regulation is possible, but currently under research)

    When put in the Frequency-Watt mode of operation, the PV system autonomously modulates its real power output depending on the grid frequency following a piece-wise-linear frequency-watt characteristics curve. Frequency disturbances in a power system mainly originate from any mismatch between real power generation and demand. Frequencies higher than nominal value occur if the generation is more than the demand and frequencies lower than the nominal value occur if the generation is less than the demand. Power plants can reduce their output in the event of higher frequency (down regulation) or increase their output in the event of lower frequency (up regulation) in order to support the power system frequency.

    Typically, while in Frequency-Watt mode, the PV system provides down regulation by curtailing real power when the frequency goes higher than the nominal value. Up regulation by the PV system is also possible, but the techniques to do so are not yet matured. The default configuration of the characteristics curve can be adopted from existing standards (e.g., IEEE P1547). The frequency-watt characteristics curve has to be configurable remotely or locally in the allowable range specified by the adopted standard.

- Volt-Watt (Typically down regulation; up regulation is possible, but currently under research)

  While in the Volt-Watt mode of operation, the PV system autonomously modulates its real power output depending on the grid voltage following a piece-wise-linear volt-watt characteristics curve. The PV system can curtail real power (down regulation) or increase real power generation (up regulation) to provide voltage support while in Volt-Watt mode as specified by existing standards (e.g., IEEE P1547).

  Typically, while in Volt-Watt mode, the PV system curtails the real power to support the grid voltage (down regulation). Up regulation by the PV system is also possible but the techniques for doing so are not yet matured. The default configuration of the characteristics curve can be adopted from existing standards (e.g., IEEE P1547). The volt-watt characteristics curve should be configurable remotely or locally in the allowable range specified by the adopted standard.

- Var capability and modes (IEEE P1547)

  The var modes of PV systems for grid services focus on different ways of injecting or absorbing reactive power by PV systems depending on various remote/local signals and grid conditions. Existing standards, e.g., IEEE P1547, can be followed for determining the response time and ramp rate for reactive power change under different var modes and also for determining the required var capability of the PV systems.

  - Fixed power factor

    The PV system will run autonomously maintaining a specific power factor while in fixed power factor mode.

  - Fixed var

    The PV system will inject or absorb a fixed reactive power while in fixed var mode. When the PV system is running in fixed var mode, the real power output from the PV system may have to be reduced to maintain the required reactive power output.

  - Volt-var

    The PV system has to be able to autonomously modulate its reactive power output depending on the grid voltage following a piece-wise-linear volt-var characteristics curve. The default configuration of the characteristics curve can be adopted from existing standards (e.g., IEEE P1547). The volt-var characteristics curve has to be configurable remotely or locally in the allowable range specified by the adopted standard. The PV system may run simultaneously both in Volt-Watt and Volt-Var modes to provide better grid service.

C.3 Equipment Availability and Usage Patterns

As mentioned earlier, active power availability of PV systems is highly dependent on solar irradiance and temperature along with other weather parameters. The conventional way of operating PV systems is to put them in MPP mode. Recent versions of standards and grid codes require them to provide additional grid services, i.e., voltage regulation, frequency regulation, etc. However, if those regulations demand that active power needs to be modulated, then active power modulation is possible only during daylight hours. On the other hand, PV systems with the feature of so-called night mode can modulate reactive power even at night with no sunlight.

C.4 Change in Power Output Resulting from Response

The details can be found in Section C.2.

C.5 Device Model

A model of PV arrays with an inverter that will interface with the generic Battery-Equivalent Model for grid services is presented in Figure C.1. The details of the interaction between the device model (PV system with inverter) and the battery-equivalent grid service model can be found in Chapters 1 and 2 of this document. Each of the components of the model of the PV arrays with inverter is described below.

- MPP Estimation

  To provide dispatch service from the PV system, forecasting of power output from the PV is required. It is assumed in this model that the forecasted irradiance and temperature are available to the owner/operator of the PV system to forecast maximum available power from the PV panels. The forecasting error needs to be accounted for to determine available power. The maximum power from the PV panels can then be used along with inverter efficiency to estimate the available maximum AC power, $P_{ac,MPP}$, from the PV system. With the knowledge of $P_{ac,MPP}$, the available maximum reactive power, Q_{Max} to/from the inverter can be calculated using Equation (C.1):

  $$Q_{Max} = \sqrt{S_{max}^2 - P_{ac,MPP}^2} \quad \text{(C.1)}$$

  where S_{max} is the rated apparent power of the inverter. The maximum available real/reactive powers are then used in the “Limit Check” block described below.

- PV Model

  Solar cells in a PV system are connected in series and/or parallel in order to achieve the required voltage, current, and power levels. The power generation from a PV system is highly dependent on weather conditions and the conversion efficiency of the solar cell. Solar irradiance and temperature are the two most important weather parameters for PV generation. Other parameters that also have impact on available PV generation are sun angle, wind speed, and humidity. Available PV generation can be forecast using the forecasted weather parameters, e.g., solar irradiance and temperature, for a PV system with a known solar cell connection configuration and conversion efficiency. The solar array converts the incident solar energy into DC electrical energy.

- Inverter

  The inverter in the PV system converts the power from DC to AC in order to inject energy into the grid. The efficiency of the DC-AC power conversion of the inverter depends on the AC output power level corresponding to the inverter capacity (percent of rated AC output power of the inverter) and also on the voltage level on the DC side. The inverter can generate reactive power within its reactive power capability limit even when no real power is being converted from DC to AC. The inverter block used in this model in the “MPP estimation” block calculates the DC to AC conversion efficiency at the MPP. The inverter block in “Model of photovoltaic solar arrays with inverter” (in Figure C.1) calculates real and reactive power references based on modes of operations, looks for any limit violation in real/reactive power, and imposes ramp limits and time responses on the output real/reactive power.

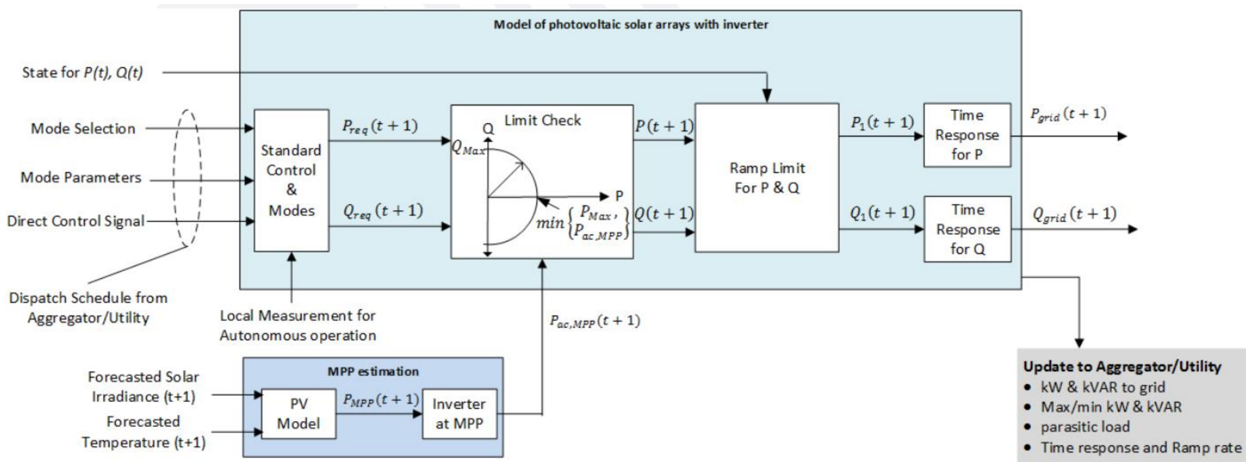

Figure C.1. Model of photovoltaic solar arrays with inverter for grid services.

- Standard Control and Modes

The PV system will have to run in different modes depending on the grid requirements to provide grid services. It is envisioned that the aggregator or utility operator will, from time to time, request PV systems to run in a specific mode, change set points or curves defining different modes, and/or send direct command signals for real and/or reactive powers. Some of the modes need local measurements of grid parameters (e.g., voltage, frequency) to run autonomously. Using the input from an aggregator, utility, or local measurements, the requested real power output (P_{req}) and reactive power output (Q_{req}) from the PV system will be calculated in the "Standard Control and Modes" block of the PV model. Predefined set points and curve settings will be used, if necessary, to calculate these requested powers. Details of these modes are described in Section 3.3.2. Figure C.2 depicts one way of implementing the mode selection. Selection of autonomous mode or direct control mode of operation will be decided by the utility through a command signal, "mode selector" as shown in Figure C.2. While in direct command mode, the aggregator/utility will send the command signal specifying the required real/reactive power generation from the inverter directly. On the other hand, in the autonomous mode of operation, the utility will set the desired autonomous mode of operation by another command, "Autonomous Operation mode selector" as depicted in Figure C.2, and the inverter will run in that mode with the help of the necessary local voltage/frequency measurement.

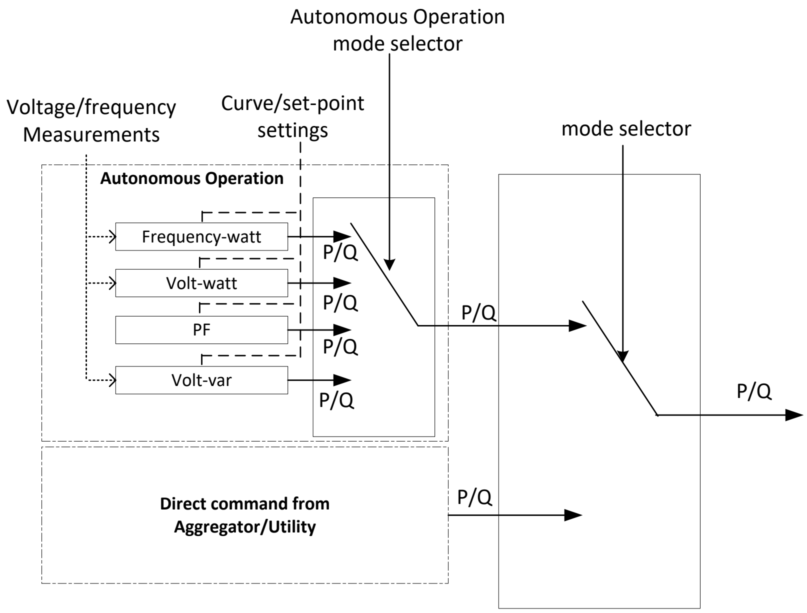

Figure C.2. Implementation of mode selection.

- Limit Check

  While providing the grid service, the PV system has to be within all limits (e.g., thermal limit, current limit) in order to maintain safety and reliability. The "limit check" block will look for any electrical limit violation in the requested real/reactive power from the inverter and will take necessary steps as recommended by the manufacturer and/or utility if any violation is found. Figure C.3 shows one way to implement the limit checks.

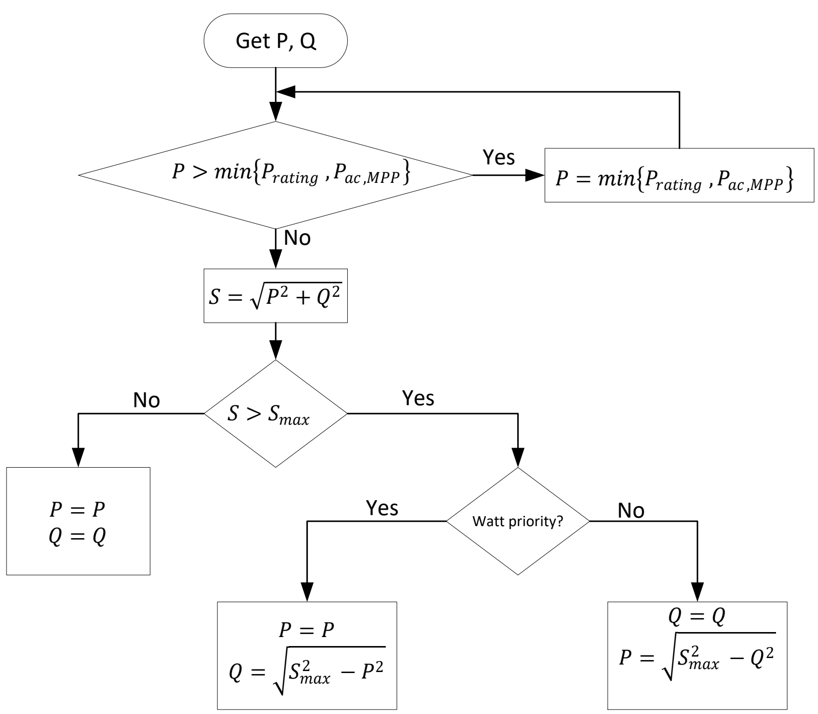

Figure C.3. Flow diagram for detection and correction of any limit violation.

The “Limit Check” block gets the information about the requested real power (P) and reactive power (Q) from the inverter as inputs. The real power generation from the inverter cannot be greater than the real power rating of the inverter, P_{rating}, or available maximum power on the AC side, $P_{ac,MPP}$. The apparent power output from the inverter cannot violate the rated apparent power rating of the inverter, S_{max}. If the requested apparent power becomes greater than S_{max}, either expected reactive power or real power have to be curtailed depending the priority of real power over reactive power or vice versa. The outputs from the limit check block are the expected real/reactive power output from the inverter for grid services.

- Ramp Limit

  Many of the inverters available on the market have an inherent ramp limit for both real and reactive power change from one level to another. Utilities and aggregators may also want to have some deliberate ramp limit for PV inverters considering safe operation of the power system. The ramp limit block will introduce the desired limit in the PV system.

- Time Response

  PV systems from different manufacturers may have different response times and time response types (first order, ramp, etc.) when the output power changes from one level to another, depending on hardware architecture and control algorithms. On the other hand, aggregators, utilities, and existing standards (e.g., IEEE P1547) also recommend having finite response times and ramp rates for PV inverters. Some of the PV inverters may also have a time delay to change the output in response to a change in input signal. The time response block in the model introduces these parameters, i.e., response time, ramp rate, and delay.

- Update to Aggregator

  The PV model will generate necessary updated information for the Battery-Equivalent Model to be used by the aggregator/utility. The information updates will consist of kW and kvar to grid, max/min kW and kvar, parasitic load, response time and ramp rate and other information deemed necessary by the aggregator or utility.

C.5.1 PV System Modeling Assumptions

The actual PV system may consist of many components, i.e., PV array, DC/DC converter, DC/AC inverter, filter, and other accessories, such as a human-machine interface. However, the model discussed here assumes that the PV/inverter system is a single distributed generation unit without going into those component details. It is also assumed that the control algorithms used in the PV system can successfully track a real/reactive power reference signal with acceptable accuracy and response time. No particular control algorithm is recommended here. This approach will keep the manufacturers open to adopting any hardware/software system that they deem appropriate, thereby paving the way for innovation, while at the same time the task of scheduling and dispatching for the aggregator/utility will be easier because they will only deal with a generic power generation model and Battery-Equivalent Model without having to deal with device-specific complexities.

To consider the PV system as a dispatchable real power source that can provide grid services, the forecasted real power generation from the PV system is assumed to be accurate enough with an acceptable error margin. It is assumed that the forecasting algorithm is embedded with the fleet of PV devices and the operator of the PV system has access to the forecasted PV generation information. Details of the forecasting method are beyond the scope of this effort.

It is also assumed that the PV system can receive commands through a proper communication channel from the aggregator/utility, act upon on those commands by changing the status or output of the PV system accordingly, and update the aggregator/utility with necessary information (e.g., kW and kvar to grid, max/min kW and kvar, parasitic load, time response and ramp rate). However, this model does not provide any recommendation about the implementation of the communication methods.

C.5.2 Parameters/Equipment Characteristics

The mathematical model parameters for the PV system model are discussed next. This list has significant overlaps with the list of already-defined parameters to be characterized, adopted parameters, and assumed parameters. Some parameters will be internal to the model and are not tested as part of the device characterization, but are listed here because they are integral to how the model operates.

This following list of values must be provided exogenously to the model. This is in contrast to variables (see next section), which are endogenously calculated values.

- continuous output power, $P_{continous}$.
- conversion efficiency (based on grid service duty cycle), $\eta_{conversion.}$
- var capability and modes – power factor, volt-var, fixed power factor (revised IEEE P1547.1 and/or UL1741 SA):[1] Discussed in Section 3.0.
- response time, $t_{response}^{var}$, and ramp rates, r_{max}^{var}, for var modes[1]:
  - watt modes – curtailment, frequency-watt, volt-watt [1]: Discussed in Section 3.0.
  - response time, $t_{response}^{watt}$, ramp rates, r_{max}^{watt}, for watt modes[1]
  - responses for watt-priority v/s var priority: Discussed in Section C.5.
- parasitic power loss, $P_{loss}^{parasitic}$
- startup ramp rate, $r_{max}^{startup}$
- kW rating (nominal condition, maximum, P_{rating}^{STC}
- kVA rating (nominal condition, maximum, S_{rating}^{STC}
- min-max operating temperature range, $T_{range}^{operating}$
- system operating ranges: The min-max operating range of AC voltage, V_{ac}^{range}, maximum DC voltage, V_{dc}^{max}, and min-max operating range of frequency, f_{range}, for the safe operation of the PV system.
- peak efficiency, η_{peak}, of inverter and the California Energy Commission (CEC) efficiency.

[1] Some of these parameters may be found in the future through interconnection testing under revised P1547.1 and/or UL1741 SA. Additional testing may be required for these parameters as needed for grid services.

C.5.3 Boundary Conditions

The model of PV solar arrays with inverter is highly dependent on the weather parameters because real power generation from a PV system depends on solar irradiance, temperature, etc. Also, grid conditions, e.g., voltage and frequency, at point of common coupling (PCC) are a significant factor in PV output when advanced grid functions are enabled.

C.5.4 Variables

Variables are values to be calculated by the model. The variables that the PV/inverter model will calculate are as follows:

- maximum power point of the PV array, $P_{MPP}(t)$
- maximum available power on the AC side of the inverter, $P_{ac,MPP}(t)$
- real power output to the grid from the PV system for grid services, $P_{grid}(t)$ in response to requested real power from the aggregator/utility or from autonomous modes, $P_{req}(t)$
- reactive power output to grid from the PV system for grid services, $Q_{grid}(t)$ in response to requested reactive power from the aggregator/utility or from autonomous modes, $Q_{req}(t)$.

C.5.5 Physical Equations

To achieve fast and efficient simulation performance, PV system models used for planning studies typically avoid the complicated nonlinear equations that describe the power generation from PV panels and subsequent complex switching models of the power electronic converters interfacing the PV generation to the grid. Detailed modeling of each PV system will also be very complicated because of the presence of different inverter technologies and proprietary control algorithms used in a PV system. Therefore, a generalized model as depicted in Figure C.1, which is applicable for grid services, will be discussed here.

The outputs of the model are the expected real/reactive power generation for the PV system under different weather parameters, e.g. solar irradiance and temperature, the control signal from the aggregator/utility, and local measurements (e.g. voltage and frequency). The model is applicable for both single phase and three-phase PV systems. The physical equations describing the model in Figure C.1 are discussed in this section.

An equivalent circuit model of PV modules can be categorized mainly into two groups: single diode models or double diode models. The single diode model consists of series and parallel resistances and performs better than the double diode model when considering accuracy and complexity (Shongwe and Hanif, 2015). Figure C.4 shows a single diode model of the PV module.

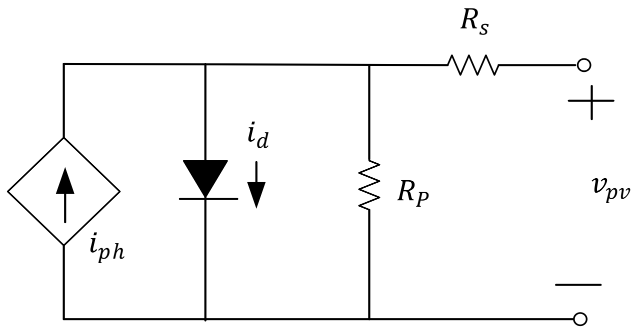

Figure C.4. Single diode model of a PV module.

The current-voltage (I-V) characteristics of the PV module depicted in Figure C.4 can be expressed as (Mahmoud, Xiao and Zeineldin, 2012):

$$I_{pv} = I_{ph} - I_s\left[e^{\left(\frac{V+R_S I}{AV_t}\right)} - 1\right] - \frac{V+R_S I}{R_P} \tag{C.2}$$

where i_{ph}, i_s and A are the current generated in the PV module for solar irradiance, reverse saturation current of the diode, and diode ideality factor, respectively. V_t is the thermal voltage of N_s series connected cells and defined as $V_t = \frac{N_s kT}{q}$ where q, k, and T are electron charge (1.6×10^{-19} C), Boltzmann constant (1.38×10^{-23} J/K), and temperature in Kelvin, respectively. For the arrays with N_P parallel connected cells, the PV current and saturation current can be calculated as $I_{ph} = I_{ph,cell}N_P$ and $I_s = I_{s,cell}N_P$. The PV current generated by solar irradiance and diode reverse saturation current are highly dependent on temperature and solar irradiance (Villalva, Gazoli and Filho, 2009).

The I-V curve for a PV module defined by Equation (C.2 contains five unknown parameters: the current generated in the PV module for solar irradiance, reverse saturation current, series and shunt resistances and diode ideality factor. Manufacturers of PV arrays mainly provide information of three operating conditions (Villalva, Gazoli and Filho, 2009; Shongwe and Hanif, 2015) at standard test conditions (STC), i.e. nominal open-circuit condition (open circuit voltage $V_{OC,STC}$ at $I = 0$), nominal short circuit condition (short circuit current $I_{sc,STC}$ at $V = 0$) and MPP voltage $V_{MPP,STC}$ and MPP current $I_{MPP,STC}$) along with current-temperature coefficient (α_T), voltage-temperature coefficient (β_T) and maximum output power, P_{max}. Numerous approaches have been proposed for the solution of the five-parameter single diode model of a PV module using the manufacturer-supplied information. This document assumes that any method with acceptable accuracy should be fine while modeling the PV module.

The power output from the PV can be calculated using Equation (C.3), as follows:

$$P_{pv} = V_{pv}I_{pv} = V_{pv} \times \left(I_{ph} - I_s\left[e^{\left(\frac{qv_{pv}}{kAT_C N_s}\right)} - 1\right]\right) \times N_P \tag{C.3}$$

The output power from PV is DC in nature. The electrical conversion efficiency, η_c, of PV modules depends on the temperature and solar irradiance and can be expressed as follows (Palyvos and Skoplaki, 2009):

$$\eta_c = \eta_{c,STC} \times \left[1 - \beta_{ref}(T - T_{STC})\right]. \tag{C.4}$$

where $\eta_{c,STC}$, T, T_{STC} , and β_{ref} are the electrical conversion efficiency of the PV array under standard test conditions (STC), actual temperature in Kelvin, temperature STC in Kelvin, and efficiency-temperature coefficient of the PV module, respectively. Values of $\eta_{c,STC}$ and β_{ref} are normally given in product datasheet.

The efficiency of the inverter, η_{inv}, while converting the power from DC to AC depends on the output power level as well as input voltage level. Using the inverter efficiency, the inverter output power, P_{AC}, at MPP can be calculated as follows:

$$P_{ac,MPP} = \eta_{inv} \times P_{MPP} \tag{C.5}$$

where $\eta_{inv} = f(P_{AC}, V_{pv})$ and P_{MPP} is the output power of the PV array at the MPP. A look-up table containing the information about inverter efficiency at various levels of output AC power and input DC voltage level can be used for modeling the PV system. Manufacturer-provided information or laboratory test results could be used to construct the look-up table. The overall efficiency of the PV system can be calculated as follows:

$$\eta_{PV} = \eta_{inv} \times \eta_c = f(P_{AC}, V_{pv}) \times \eta_{c,STC} \times [1 - \beta_{ref}(T - T_{STC})] \tag{C.6}$$

The time response of inverter output change can be of 1st order or 2nd order with some time delay. A convenient way to implement the time response is to pass the expected inverter power change through a low-pass filter that can mimic the behavior of the desired time response:

$$F(s) = \frac{w_n^2 e^{-s\tau_{delay}}}{as^2 + 2\xi w_n s + w_n^2} \tag{C.7}$$

where τ_{delay} represents the time delay. The parameters of Equation (C.7) can be tuned to achieve the time responses that actual inverters exhibit. For example, a 2nd order response can be obtained by setting $a = 1$ and putting the value of natural frequency and damping coefficient for w_n and ξ, respectively. In order to have a 1st order response, one can set $a = 0$, $w_n = 1$, and $\xi = \frac{\tau}{2}$; where τ is the 1st order response time constant.

C.5.6 End-Use Load (if any)

Not applicable.

C.5.7 Parasitic Loads (if any)

The parasitic load for PV could be any power demand to run the auxiliary system, e.g., fan to cool down the inverter, voltage/current/frequency measuring/sensing devices, communication interfaces, etc.

C.5.8 Possible Device Responses

C.5.9 Constraints on Device Response

Some constraints will impact the ability of the PV system to provide grid service. The constraints can be categorized mainly in three groups:

- End-user limits – The PV may operate at reduced power level relative to the MPP to provide grid service, thereby reducing the energy revenue for the owner of the PV system. If there is no compensation scheme, the owner may not opt to participate in providing grid service under such conditions.
- Time limits – If no energy storage is used, the real power output from PV system will not be available during nighttime. However, reactive power generation may still be possible in the absence of sunlight.
- Equipment limits – The PV system may operate longer while providing grid service (e.g. reactive power generation at night) compared to the case when no grid service is being provided. This longer run time may result in reduced reliability of the PV system. The PV system also will be subject to design constraints (e.g., current limit, thermal limit) while providing grid services.

C.5.10 Translating Device Model Parameters to Battery-Equivalent Model Parameters

The purpose of the model of photovoltaic solar arrays with inverter presented here is to create a device-specific model that can communicate with the aggregator/utility using parameters that can fit in a generic Battery-Equivalent Model. In this case, all the inputs, except the weather parameters, and the outputs of the PV model are Battery-Equivalent Model parameters. The weather parameters constitute the boundary condition for the PV model. A mapping of the PV system parameters to the Battery-Equivalent Model is presented below in Tables Table C.1 through Table C.7 (please refer to Chapter 2 for the definition of these parameters).

Table C.1. Battery-Equivalent API Variables Passed from the High-Level Model to the Device Fleet (Step 1)

Parameter	Battery-Equivalent Model	PV System
Energy storage capacity	C*	NA
Maximum power to grid (real, reactive)	$P^*_{grid.max}$ $Q^*_{grid.max}$	P^*_{rating} Q^*_{rating}
Minimum power to grid (real, reactive)	$P^*_{grid.min}$ $Q^*_{grid.min}$	P^*_{min} Q^*_{min}
Maximum power for services (real, reactive)	$P^*_{service.max}$ $Q^*_{service.max}$	P^*_{rating} Q^*_{rating}
Minimum power for services (real, reactive)	$P^*_{service.min}$ $Q^*_{service.min}$	P^*_{min} Q^*_{min}
Ramp rate, power up (real, reactive)	$\dot{P}^*_{up}$ $\dot{Q}^*_{up}$	$\dot{P}^*_{up}$ $\dot{Q}^*_{up}$
Ramp rate, power down (real, reactive)	$\dot{P}^*_{down}$ $\dot{Q}^*_{down}$	$\dot{P}^*_{down}$ $\dot{Q}^*_{down}$
Charging efficiency	e^*_{in}	NA
Discharging efficiency	e^*_{out}	η_{PV}

Table C.2. Battery-Equivalent API Variables Passed from the High-Level Model to the Device Fleet (Step 1)

Parameter	Battery-Equivalent Model	PV System
Power requested for service (real, reactive)	$P_{req}(t_0)$ $Q_{req}(t_0)$	$P_{req}(t_0)$ $Q_{req}(t_0)$

Table C.3. Battery-Equivalent API Variables Available from Topological and Geographical Information Busses

Parameter	Battery-Equivalent Model	PV System
Rate for power (real, reactive)	$R_{real}(t_0)$ $R_{reactive}(t_0)$	$R_{real}(t_0)$ $R_{reactive}(t_0)$
Service voltage at device	$V_{ratio}(t_0)$	$V_{ratio}(t_0)$
Outdoor temperature at device	$T_{out}(t_0)$	$T_{out}(t_0)$
Total solar horizontal radiation at device	$H_{solar}(t_0)$	$H_{solar}(t_0)$
Service water temperature	$T_{h2o}(t_0)$	NA
Service frequency at device	$f(t_0)$	$f(t_0)$

Table C.4. Battery-Equivalent API Variables Passed from the Device Fleet to the High-Level Model (Step 4a) for the Time Step

Parameter	Battery-Equivalent Model	PV System
Power to grid (real, reactive)	$P_{grid}(t_0)$ $Q_{grid}(t_0)$	$P_{grid}(t_0)$ $Q_{grid}(t_0)$
Power delivered for service (real, reactive)	$P_{service}(t_0)$ $Q_{service}(t_0)$	$P_{service}(t_0)$ $Q_{service}(t_0)$
Energy stored	$E(t_0)$	NA

Table C.5. Battery-Equivalent API Constraint Variables Passed from the Device Fleet to the High-Level Model (Step 4b) for the Next Time Step

Parameter	Battery-Equivalent Model	PV System
Energy storage capacity	$C(t_1)$	n/a
Maximum power to grid (real, reactive)	$P_{grid.max}(t_1)$ $Q_{grid.max}(t_1)$	$P_{ac,MPP}(t_1)$ $Q_{.max}(t_1)$
Minimum power to grid (real, reactive)	$P_{grid.min}(t_1)$ $Q_{grid.min}(t_1)$	$P_{min}(t_1)$ $Q_{min}(t_1)$
Maximum power for service (real, reactive)	$P_{service.max}(t_1)$ $Q_{service.max}(t_1)$	$P_{ac,MPP}(t_1)$ $Q_{.max}(t_1)$
Minimum power for service (real, reactive)	$P_{service.min}(t_1)$ $Q_{service.min}(t_1)$	$P_{min}(t_1)$ $Q_{min}(t_1)$
Ramp rate, power up (real, reactive)	$\dot{P}_{up}(t_1)$ $\dot{Q}_{up}(t_1)$	$\dot{P}_{up}(t_1)$ $\dot{Q}_{up}(t_1)$
Ramp rate, power down (real, reactive)	$\dot{P}_{down}(t_1)$ $\dot{Q}_{down}(t_1)$	$\dot{P}_{down}(t_1)$ $\dot{Q}_{down}(t_1)$
Charging efficiency	$e_{in}(t_1)$	NA
Discharging efficiency	$e_{out}(t_1)$	η_{PV}

Parameter	Battery-Equivalent Model	PV System
Time limit, hold	$\Delta t_{hold}(t_1)$	$\Delta t_{hold}(t_1)$
Time, restoration	$t_{restore}(t_1)$	$t_{restore}(t_1)$
Strike price	$SP(t_1)$	$SP(t_1)$
State-of-charge cost		
Maximum service requests	$N_{req}(t_1)$	NA

Table C.6. Other Battery-Equivalent Model's Variables (Not Passed through the API)

Parameter	Battery-Equivalent Model	PV System
Power discharged (real, reactive)	$P_{discharge}(t)$ $Q_{discharge}(t)$	NA
Power output from source (real, reactive)	$P_{output}(t)$ $Q_{output}(t)$	$P_{grid}(t_0)$ $Q_{grid}(t_0)$
Power to grid, base case (real, reactive)	$P_{grid.base}(t)$ $Q_{grid.base}(t)$	$P_{ac,MPP}(t_1)$ $Q_{.max}(t_1)$
Load	$P_{load}(t)$	0
Base load	$P_{load.base}(t)$	0

Table C.7. Characteristics of the Battery-Equivalent Model for Various Device Classes

Battery-Equivalent Characteristic	PV Solar/Inverter
Source / Sink	PV array
Energy Storage Capacity (C)	NA (infinite)
State of Charge (SoC)	NA
Converter	AC inverter
Charging Efficiency	NA
Discharging Efficiency	Inverter discharging efficiency
Power to End Use	NA
Parasitic Power	Power for controls
Power Discharge	NA
Power Output	Inverter AC power discharge
Power Conserved	NA
Power to Service	Difference in AC power output from the device fleet compared to the base case

C.5.11 Device Impact Metrics

None

C.5.11.1 Energy Impact Metrics

The energy impact of providing grid services using PV systems is defined by how much energy is not being injected into grid while providing grid services compared to the test case of running the PV at the MPP.

C.5.11.2 Amenity Impacts Metrics

None

C.5.11.3 Equipment Impacts Metrics

PV inverters may have to run longer beyond the hours when there is no sun in order to supply reactive power. Even during the time with sun, the inverter may have to run close to rated volt-ampere (VA) capacity in order to provide both real and reactive power. Providing reactive power thus places an extra burden on the inverter, reducing its lifetime and increasing the lifecycle cost.

C.6 Device Fleet

C.6.1 Default Fleet Characteristics (Instantiation)

Instantiation is required to get the baseline power or PV fleet before any service can be provided. Cumulative maximum power at any given time of all the PVs grouped as one fleet is the baseline power of the fleet:

$$P_{base}^{Fleet}(t) = \sum_{i=1}^{N} P_{MPP}^{i}(t) \tag{C.8}$$

where N is the total number of PV system in the fleet, $P_{MPP}^{i}(t)$ is the MPP of *i*-th PV system at time *t*, and $P_{base}^{Fleet}(t)$ is the baseline power of PV system at time *t*. It is important to note that, even if all the PV system in a fleet are of similar ratings, it may be found that $P_{MPP}^{i}(t) \neq P_{MPP}^{j}(t)$ when both *i*-th and *j*-th PV systems are in the same fleet. The reason of this is that *i*-th and *j*-th PV system may experience different weather conditions. However, for simplicity, it can be assumed that $P_{MPP}^{i}(t) \approx P_{MPP}^{j}(t)$ when *i*-th and *j*-th PV system are of similar rating and located in close proximity to one another. The baseline case of PV fleet will change whenever there is a change in weather condition.

C.6.2 Coordination Scheme

Once the baseline condition is known, any active power request to the PV fleet must be equal or lower than the PV fleet baseline power. On the other hand, a reactive power request to the PV fleet has to make sure that there is no violation of the apparent power rating of the PV fleet. These conditions can be expressed as follows:

$$P_{req}(t) \leq P_{base}^{Fleet}(t) \tag{C.9}$$

$$\sqrt{P_{req}^{2}(t) + Q_{req}^{2}(t)} \leq S_{rating}^{Fleet} \tag{C.10}$$

where S_{rating}^{Fleet} is the apparent power rating of the PV fleet.

C.6.3 Example Usage

The simulation result of 1,000 units of PV systems grouped together to form a PV fleet is shown in Figure C.5. Each of the units is rated for a maximum of 255 W. As can be seen in the figure, the fleet injects active power to the grid as long as the requested power is within the maximum power availability of the fleet. If the requested power exceeds the maximum power availability, the fleet injects only the power it can generate at that point in time. Also, because PV systems cannot generate negative power (consume power), all negative power requests are ignored.

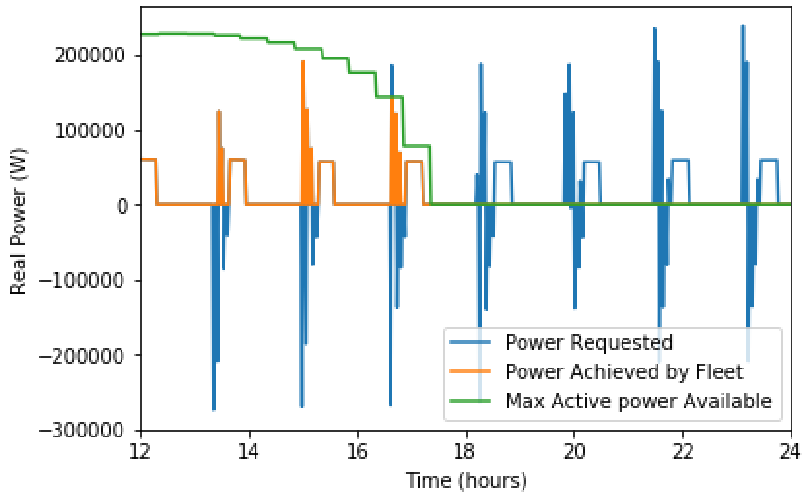

Figure C.5. Simulation result of 1,000 units of PV systems grouped together to form a PV fleet.

C.7 References

Mahmoud, Y., Xiao, W. and Zeineldin, H. H. (2012) ‘A Simple Approach to Modeling and Simulation of Photovoltaic Modules’, IEEE Transactions on Sustainable Energy, 3(1), pp. 185–186.

Palyvos, J. A. and Skoplaki, E. (2009) ‘On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations’, Solar Energy, 83(5), pp. 614–624.

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Appendix D – Battery Inverters

D.1 Basic Device Purpose

Batteries are designed to store electrical energy. The increasing variation in time value of energy has driven the use of batteries as controllable distributed energy resources (DERs). This is enabled through the use of low-cost power electronic inverters that can precisely control charge and discharge. This appendix describes the software implementation of an open-source battery-inverter fleet model in Python. The *BatteryInverterFleet* class model can be used by scientists, researchers, and engineers to perform simulations of one or more fleets of similar battery-inverter systems connected to the grid. The program tracks the state of charge (SoC) of the simulated batteries and ensures that they stay within their limits, while responding to separately generated service requests to charge or discharge. The model can be used to analyze control and coordination, placement and sizing, and many other problems associated with the integration of batteries on the power grid.

The scope of this work was to develop and validate the source code for modeling a fleet of battery-inverter devices. Also referred to as battery energy storage systems (BESSs), these devices can act as loads, power sources, and even as transmission or distribution assets depending on how they are operated. Batteries store electrical energy as chemical energy and, when connected to the grid by power electronic-based inverters, are extremely flexible in responding to power commands issued by utilities or markets. However, they are physically limited in how much energy they can supply or absorb, meaning that an operator must carefully decide when and how much to charge/discharge to maximize the benefits being supplied. These energy limits are the primary focus of our modeling efforts.

D.2 Standard Controls and Normal Operational Modes

TBD

D.3 Equipment Availability and Usage Patterns

TBD

D.4 Change in Power Output Resulting from Response

TBD

D.5 Device Model

D.5.1 Assumptions and Physical Equations

The battery-inverter model is implemented in two ways: via the energy reservoir model (ERM) and the charge reservoir model (CRM). ERM is a term for the class of SoC models that define capacity in units of energy (kWh). These models are highly efficient for simulation but can be inaccurate over large changes in SoC. ERMs are widely used in research on the integration of energy storage with the grid. This includes studies using ERMs that ignore efficiency losses

(Donadee and Ilic 2014; Donadee and Wang 2014; Perez et al. 2013), including both charge and discharge efficiencies (EPRI 2011; Erseghe et al. 2014; Huang et al. 2014; Jayasekara et al. 2016; Suazo-Martinez et al. 2014; Tant et al. 2013; Wang et al. 2014; Zeng et al. 2014), and those that include some form of self-discharge power (EPRI 2011; GridLAB-D 2018; Macedo et al. 2014; Malysz et al. 2014; Wen et al. 2016). The ERM implementation used in the battery-inverter model is shown below:

$$\varsigma_{min} \leq \varsigma \leq \varsigma_{max}$$

$$p_{min} \leq p_e \leq p_{max} \tag{D.1}$$

where

ς = the SoC,
p_e = the AC power (+ charge, - discharge),
Q_{cap} = the energy capacity,
η_e = the energy efficiency,
p_{sd} = the self-discharge power, and
ς_{min}, ς_{max}, p_{min}, and p_{max} = the SoC and power limits respectively.

CRM is a term used for the class of BESS models that define capacity in units of charge (Ah). These models are less computationally efficient than ERMs, but they have a higher potential for accuracy based on the increased number of represented battery dynamics. CRMs are also widely used in the scientific literature. This includes studies using CRMs that ignore coulombic efficiency (Abdeltawab and Mohemed 2015; Feng et al. 2014; WECC 2016; Xiong et al. 2011) and those that include some form of self-discharge current (Gee et al. 2013; Teleke et al. 2010; Wang et al. 2016). The CRM implementation used in the battery-inverter model is shown below:

$$p_{dc} = i_{bat} v_{bat}$$

$$v_{oc} = f(\varsigma)$$

$$\dot{v}_1 = \frac{-1}{R_1 C_1} v_1 + \frac{1}{C_1} i_{bat}$$

$$\dot{v}_2 = \frac{-1}{R_2 C_2} v_2 + \frac{1}{C_2} i_{bat}$$

$$v_{bat} = v_{oc} + R_0 i_{bat} + v_1 + v_2 \tag{D.2}$$

$$C_{cap} \dot{\varsigma} = \eta_c max(i_{bat}, 0) + min(i_{bat}, 0) + i_{sd}$$

$$\varsigma_{min} \leq \varsigma \leq \varsigma_{max}$$

$$p_{min} \leq p_e \leq p_{max}$$

$$i_{min} \leq i_{bat} \leq i_{max}$$

$$v_{min} \leq v_{bat} \leq v_{max}$$

where

ς = the SoC,
p_e = the alternating current (AC) power (+ charge, - discharge),

p_{dc} = the direct current (DC) power,
i_{bat} = the current provided to battery system (+ charge, - discharge),
v_{bat} = the battery terminal voltage,
v_{oc} = the battery open-circuit voltage,
v_1 = the first battery dynamic voltage, and
v_2 = the second battery dynamic voltage.

The parameters in Equation (D.2) above are as follows:

ϕ0, ϕ1, and ϕ2 = the coefficients of a quadratic AC/DC conversion efficiency curve fit;
f(ς) = defined to be a `Linear', `Quadratic', `Cubic', or `CubicSpline' function (along with the associated coefficients);
R0, R1, C1, R2, and C2 = the equivalent circuit parameters;
Ccap = the charge capacity;
ηc = the coulombic efficiency; and
isd = the self-discharge current.

The constraints, ς_{min}, ς_{max}, p_{min}, p_{max}, i_{min}, i_{max}, v_{min}, and v_{max} are the SoC, power, current, and voltage limits, respectively.

Both models have additional constraints to handle limits on power factor (p.f.), apparent power, and ramp rate. In the order, ramp rate, absolute P or Q limits, apparent power limit, then power factor limits, the algorithm first checks if any of these limits are violated and, if they are, it changes the power requested of a given device to the closest value that satisfies the constraint. For the apparent power limit, the fleet model can be configured to either favor real power (P priority) or reactive power (Q priority). For P priority, if the apparent power limit is exceeded, the device will reduce its reactive power until the apparent power limit is satisfied. For Q priority, if the apparent power limit is exceeded, the device will reduce its real power until the apparent power limit is satisfied.

D.5.2 Autonomous Operation

Autonomous responses to local grid conditions are configured to match the 2018 Institute of Electrical and Electronics Engineers (IEEE) 1547 Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces (IEEE 2018). The frequency/power function is implemented using the following two equations.

Operation for low-frequency conditions:

$$p = \min_{f<60-db_{\mathrm{UF}}} \{p_{\mathrm{pre}} + \frac{(60-db_{\mathrm{UF}})-f}{60k_{\mathrm{UF}}}; p_{\mathrm{avl}}\}. \tag{D.3}$$

Operation for high-frequency conditions:

$$p = \min_{f>60+db_{\mathrm{OF}}} \left\{p_{\mathrm{pre}} + f - \frac{(60-db_{\mathrm{OF}})}{60k_{\mathrm{OF}}}; p_{\mathrm{min}}\right\} \tag{D.4}$$

where

p	=	the active power output,104 in p.u. of the DER nameplate active power rating;
pavl	=	the available active power, in p.u. of the DER rating;
ppre	=	the pre-disturbance active power output, defined by the active power ;output at the point of time the frequency exceeds the deadband, in p.u. of the DER rating;
pmin	=	the minimum active power output due to DER prime mover constraints, in p.u. of the DER rating;
dbOF	=	a single-sided deadband value for high-frequency, in Hz;
dbUF	=	a single-sided deadband value for low-frequency, in Hz;
kOF	=	the per-unit frequency change corresponding to 1 per-unit power output change (frequency droop), unitless; and
kUF	=	the per-unit frequency change corresponding to 1 per-unit power output change (frequency droop), unitless.

The volt/var function is implemented through a linear interpolation between (V_{set}, Q_{set}) points supplied in the fleet configuration. While there are many ways to specify a volt/var function curve, (V,Q) points are compatible and consistent with the methods used in IEC61850-90-7 (IEC 2013) and IEEE 1547 (IEEE 2018). The plot in Figure D.1 shows an example of how to use (V,Q) points to define a volt/var curve.

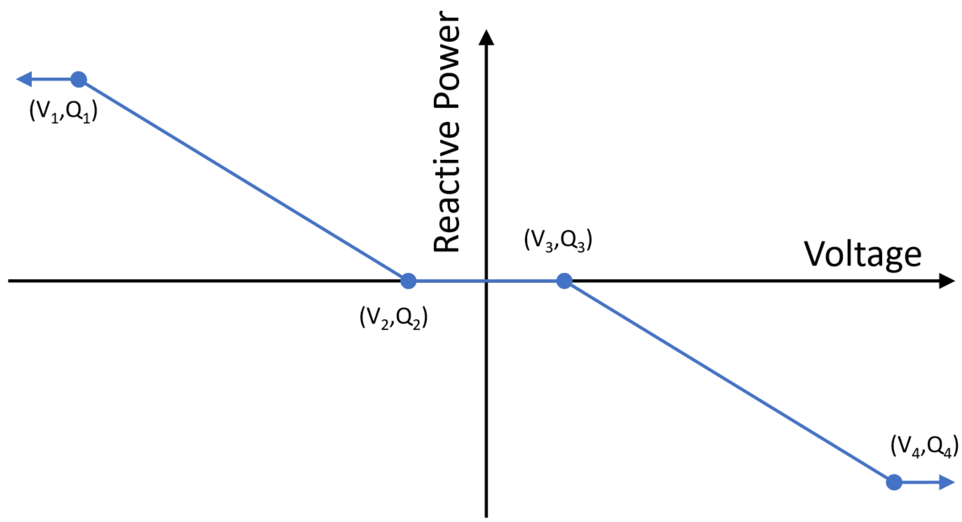

Figure D.1. Autonomous volt/var function example curve.

Whenever the fleet is configured for autonomous operation, each device in a fleet will use the GridInfo class to look up the frequency and voltage of the location assigned to it and use these functions to modify their real and reactive power.

D.5.3 Autonomous Operation Model Validation

The Autonomous Operation Model discussed above was validated by running it on a frequency and voltage profile. The same frequency was used for all devices, whereas two locations with different voltage profiles were used. The default parameters had to be changed to be more sensitive because the voltage and frequency were otherwise close enough to nominal to stay within the dead-bands for each respective function. The frequency and fleet real power response are shown in Figure D.2, and the voltages and fleet reactive power response are shown in Figure D.3.

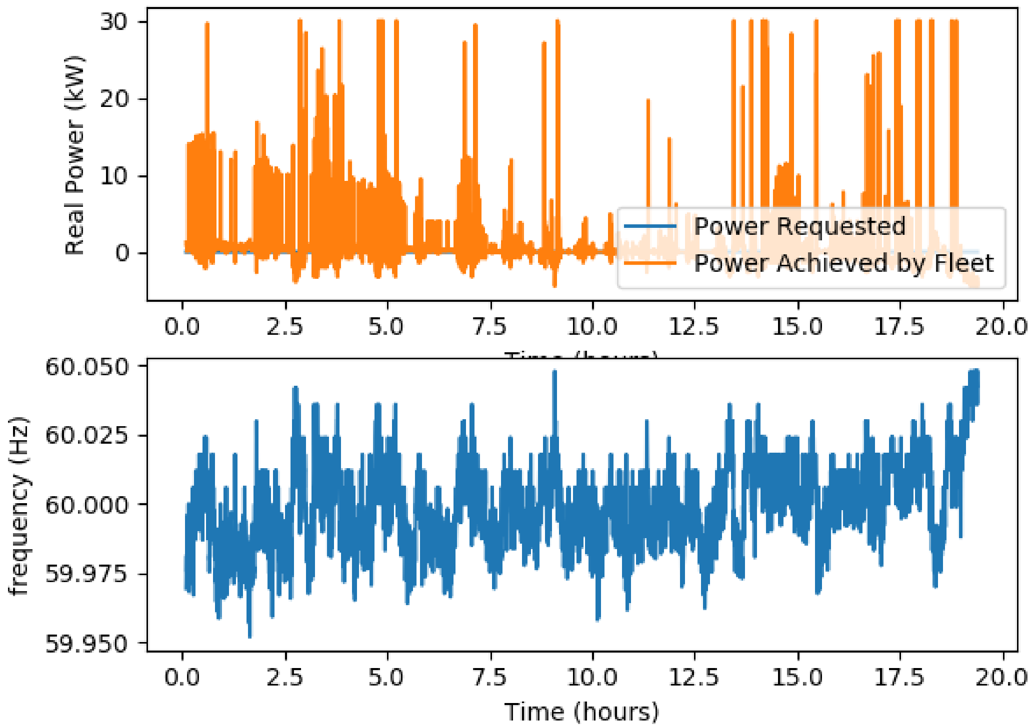

Figure D.2. Frequency/watt functionality.

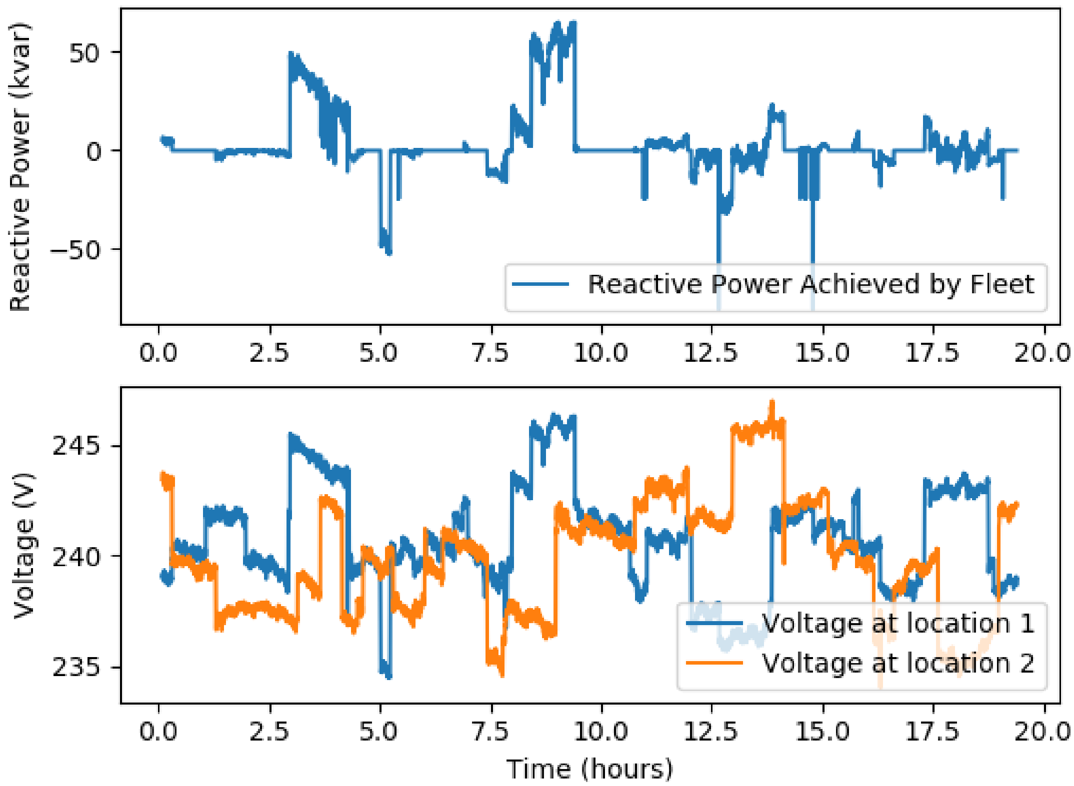

Figure D.3. Volt/var functionality.

D.5.4 Parameters/Equipment Characteristics

Model parameters are implemented in the `config.ini' file. Changing parameter values in this file will implement the changes when the *BatteryInverterFleet* is constructed. The general fleet parameters are listed in

Table D.1, the fleet configuration parameters including those for autonomous operation are listed in Table D.1, the ERM-specific parameters are listed in Table D.2, the CRM-specific parameters are listed in Table D.3, and the fleet impact metric parameters are listed in Table D.4.

Table D.1. General fleet parameters.

Name	Default Value	Description
Name	TestBat	Fleet Name
ModelType	ERM	Can be specified as ERM or CRM, defines which model is used to simulate the fleet.
MaxPowerCharge	7	Maximum charge power limit (kW)
MaxPowerDischarge	-7	Maximum discharge power limit (kW)
MaxApparentPower	7	Maximum apparent power limit (kVA)
MinPF	1	Minimum power factor [0,1]
MaxSoC	95	Maximum state-of-charge (SoC) limit
MinSoC	19	Minimum SoC limit
MaxRampUp	7	Maximum ramp rate for decreasing discharge or increasing charge power (kW/time step)
MaxRampDown	-7	Maximum ramp rate for increasing discharge or decreasing charge power (kW/time step)
NumberOfDevices Locations	30, 0,0,1	The number of battery-inverter devices in the fleet location designations for each device (positive integers), 0 if not specified
FleetModelType	Standard Normal SoC Distribution	Defines the starting SoC for each device in the fleet. Options: Uniform, Standard Normal SoC Distribution. If Uniform is specified, all devices will start with the same SoC equal to the initial state \`soc' defined below. If Standard Normal SoC Distribution is specified then each starting device's SoC will be randomly assigned from a standard normal probability density function defined by a mean, defined by the initial state \`soc' defined below, and a standard deviation, specified by \`SOC$_$STD' defined below.
SOC_STD	10	Optional parameter for standard deviation in starting SoC.
t	0	Initial time
soc	95	Initial SoC, or the mean value of the distribution for initial SoCs for devices

Table D.1. Fleet configuration parameters.

Name	Default Value	Description
is_P_priority	True	When the apparent power limit is exceeded, this Boolean variable indicates if the real power is prioritized (True) or if reactive power is prioritized (False)
is_autonomous	True	This Boolean variable either enables (True) or disables (False) all autonomous operation functions
FW21_Enabled	True	Frequency/watt operation function enable (True) or disable (False)
db_UF	0.0036	Single-sided deadband value for low-frequency, in Hz
db_OF	0.0036	Single-sided deadband value for high-frequency, in Hz
k_UF	0.005	Per-unit frequency change corresponding to 1 per-unit power output change (frequency droop), unitless
k_OF	0.005	Per-unit frequency change corresponding to 1 per-unit power output change (frequency droop), unitless
P_avl	1	Available active power, in p.u. of the DER rating
P_min	-1	Minimum active power output due to DER prime mover constraints, in p.u. of the DER rating
P_pre	0	
VV11_Enabled	True	Volt/var operation function enable (True) or disable (False)
Vset	232.8, 237.6, 242.4, 247.2	This parameter is a list of voltages corresponding to the list of vars in Qset. When enabled these points define the volt/var curve that the devices will follow when not supplied a reactive power request by a service (q = none).
Qset	3.5, 0, 0, -3.5	This parameter is a list of vars corresponding to the list of voltages in Vset.

Table D.2. ERM-specific parameters.

Name	Default Value	Description
EnergyCapacity	5.9441	Energy capacity (kWh)
EnergyEfficiency	0.6788	Round-trip energy efficiency (%)
SelfDischargePower	0	Self-discharge power (kW)

Table D.3. CRM-specific parameters.

Name	Default Value	Description
InvName	TestInv	Inverter name
InvType	TestType	Inverter type (descriptive)
Coeff0	-0.0721	Quadratic coefficient for DC power to AC power conversion function
Coeff1	0.99107	Linear coefficient for DC power to AC power conversion function
Coeff2	-0.0151	Offset coefficient for DC power to AC power conversion function
BatName	TestBat	Battery name
BatType	LiIon	Battery type (descriptive)

Name	Default Value	Description
NCells	14	Number of cells in the battery string (for multiple parallel strings, multiply charge capacity `ChargeCapacity' and divide ohmic resistance `R0' by number of strings)
VOCModelType	Cubic	Open-circuit voltage function type. Options: `Linear', `Quadratic', `Cubic', or `CubicSpline'[1].
VOC_Model_A	0.962857	Cubic coefficient for open circuit voltage
VOC_Model_B	-0.71714	Quadratic coefficient for open circuit voltage
VOC_Model_C	0.41	Linear coefficient for open circuit voltage
VOC_Model_D	3.445	Offset coefficient for open circuit voltage
MaxCurrentCharge	150	Maximum charge current limit (A)
MaxCurrentDischarge	-150	Maximum discharge current limit (A)
MaxVoltage	4.2	Maximum battery cell voltage limit (V)
MinVoltage	3.3	Minimum battery cell voltage limit (V)
ChargeCapacity	135.2366	Charge capacity (Ah)
CoulombicEfficiency	0.9462	Coulombic efficiency (%)
SelfDischargeCurrent	0	Self-discharge current (A)
R0	0.001096	Per-cell ohmic (DC) resistance (Ω)
R1[(a)]	1E+09	Per-cell resistance from diffusion time constant (Ω)
R2[(a)]	1E+09	Per-cell capacitance from diffusion time constant (F)
C1[(a)]	1E+09	Per-cell resistance from cell capacitance time constant (Ω)
C2[(a)]	1E+09	Per-cell capacitance from cell capacitance time constant (F)

(a) Setting these values to be very large effectively ignores the dynamic components in the simulation model.

Table D.4. Fleet impact metric parameters

Name	Default Value	Description
eol_cost	6000	Anticipated cost to be incurred at end-of-life. Should include both battery replacement/refurbishment costs as well as any revenue from second-life use resale ($)
Cycle_life	10000	Cycle-life, number of cycles from state of health (SoH) = 100% to SoH = 0% (#)
soh	100	Initial SoH (%)

[1] If `Linear' is specified, will use VOC_Model_M and VOC_Model_b parameters to specify slope and intercept.
If `Quadratic' is specified, will use VOC_Model_A, VOC_Model_B and VOC_Model_C parameters for the quadratic, linear, and offset coefficients respectively.
If `Cubic' is specified, will use VOC_Model_A, VOC_Model_B, VOC_Model_C, and VOC_Model_D parameters for the cubic, quadratic, linear, and offset coefficients respectively.
If `CubicSpline' is specified, will read in comma-separated parameter lists in VOC_Model_A, VOC_Model_B, VOC_Model_C, and VOC_Model_D to specify the cubic, quadratic, linear, and offset coefficients within each SoC range specified in the comma-separated list in VOC_Model_SOC_LIST. The `CubicSpline' function is configured to work with the MATLAB `spline' function meaning that the beginning of each SoC range is subtracted from the SoC value before the cubic function is applied.

D.5.5 Variables

[Describe the variables that will be used in the physical equations describing the water heater operation. (e.g., tank temperature, thermostat temperature, element power draw, ambient temperature (if a variable in model)]

D.5.6 Boundary Conditions

[Describe any boundary conditions that affect the device model. E.g., minimum and maximum water heater temperature.]

The boundary conditions considered in this model are as follows:

D.5.7 End-Use Load (if any)

D.5.8 Parasitic Loads (if any)

D.5.9 Possible Device Responses

D.5.10 Constraints on Device Response

D.5.11 TBD **Translating Device Model to Battery-Equivalent Model Parameters**

D.5.12 Device Fleet Impact Metrics

This section describes how battery aging metrics are calculated. The simplest approach to calculating the rate of degradation in batteries (ϱ) is to assume that it is a linear function of cycle throughput. Under this assumption, degradation can be modeled as being proportional to the absolute value of the battery power when using the ERM (Ebbesen et al. 2012; Jayasekara et al. 2016; Tant et al. 2013) or to the absolute value of the battery current when using the CRM (Moura at al. 2013; Perez et al 2017; Riffonneau et al. 2011.)

ERM Method:

$$\dot{\varrho} = \frac{|p_e|}{(1+\frac{1}{\eta_e})L_{\text{cyc}}Q_{cap}} \tag{D.5}$$

CRM Method:

$$\dot{\varrho} = \frac{|i_{bat}|}{\left(1+\frac{1}{\eta_c}\right)L_{\text{cyc}}C_{cap}} \tag{D.6}$$

where

p_e = AC real power,
i_{bat} = the battery current,
η_c = the coulombic efficiency,

L_{cyc} = the rated cycle-life to end-of-life (EoL),
Q_{cap} = the energy capacity, and
C_{cap} = the charge capacity.

Note that, when adding this up over a discrete simulation time, this form of degradation is equivalent to calculating the ℓ_1 norm power as shown in Equation (D.5) for Cycle-Counting ERM or the ℓ_1 norm current as shown in Equation (D.6) for Cycle-Counting CRM. The regularization weight Π_{cyc} has units of \$/kW or \$/A depending on which equation it is in because of the units of the relevant decision variable.

$$\Pi_{\text{cyc}} = \frac{\Delta t C_{\text{EoL}}}{(1+\frac{1}{\eta_e})L_{\text{cyc}}Q_{cap}} \tag{D.7}$$

$$f_b(i_{bat}) = \Pi_{\text{cyc}}\left\|i_{bat}\right\|_1 \tag{D.8}$$

where $$\Pi_{\text{cyc}} = \frac{\Delta t C_{\text{EoL}}}{(1+\frac{1}{\eta_e})L_{\text{cyc}}Q_{cap}}$$

$$f_b(i_{bat}) = \Pi_{\text{cyc}}\left\|i_{bat}\right\|_1$$

where f_b is the fleet impact metric based on battery degradation, Δt is the length of the simulation time step, and C_{EoL} is the anticipated EoL cost (although the capital cost of the BESS can also be used).

D.5.12.1 Energy Impact Metrics

[Refer to adoption of standard device energy metrics (or, if not, define yours here). Brief discussion of device’s potential energy impacts.]

D.5.12.2 Amenity Impacts Metrics

D.5.12.3 Equipment Impacts Metrics

D.6 Device Fleet Response

D.6.1 Fleet Instantiation

In this section, we introduce the *BatteryInverterFleet* class and explain its methods. The illustration in Figure D.4 shows the full list of available methods and roughly how they connect to each other. The *GridInfo* class can be constructed by passing it the name of a csv file that contains time, frequency, and voltage data in the correct format. The *BatteryInverterFleet* then takes two inputs to construct a *GridInfo* object, and a string designating which SoC model to use (either ERM or CRM). The `__init__' method opens the local *config.ini* file to extract the parameters for the appropriate SoC model and all other fleet parameters. The SoC models are described in Section D.5.1. A full list of fleet model parameters can be found in Section D.5.4.

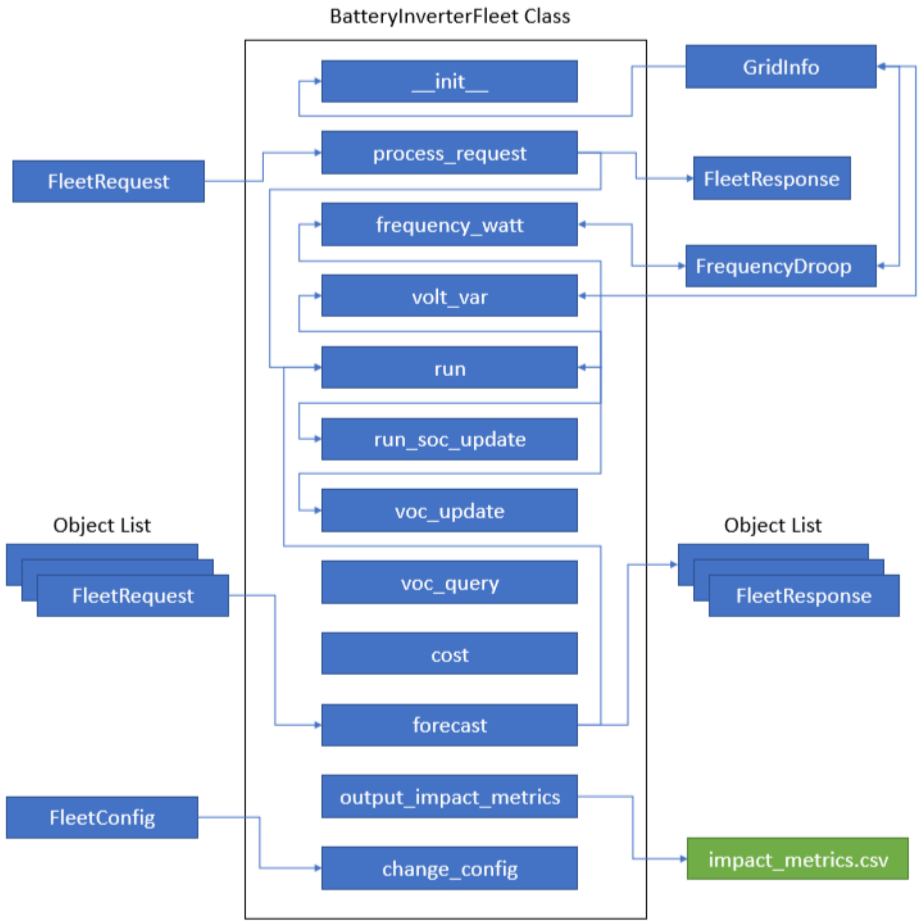

Figure D.4. BatteryInverterFleet class method diagram.

Once a *BatteryInverterFleet* is constructed, its primary interface is through the `*process_request*' method. This method accepts a `*fleet_request*' object, and returns a `*fleet_response'* object by calling the run method internally. Using the `*process_request*' method in this way also updates the internal fleet states according to the model used. A secondary interface is through the `forecast' method that accepts a list of `*fleet_request*' objects that make up a proposed schedule. This method then returns a list of *'fleet_response'* objects, corresponding to the forecast fleet response, without changing the internal states of the fleet.

The configuration file contains parameters to enable or disable autonomous operation. When autonomous operation is disabled, the *BatteryInverterFleet* will only respond to fleet requests. When enabled, the *BatteryInverterFleet* will still respond to fleet requests but the requests may be modified based on grid conditions. The *BatteryInverterFleet* has the option for two kinds of autonomous operation functions: frequency/watt and volt/var. These functions are described in Section D.5.2. Note that the `*change_config'* method will accept a *FleetConfig* object to programmatically change the parameters for autonomous operation.

The *BatteryInverterFleet* will keep track of how many cycles each device has undergone during operation and the corresponding state of health (SoH). The SoH, along with the incremental cost associated with degradation in SoH are saved to a csv file when the `*output_impact_metrics'* method is called. These calculations are described in Section D.5.12.

The `cost' method is intended for use in schedule optimization. It accepts an initial SoC, a final SoC, and a time difference between them. It returns the power required to go from initial to final SoC in the allotted time and any associated costs. The cost is calculated the same as in the `output_impact_metrics' method and is associated with the cycle-life and EoL costs. The `cost' method also returns an Able variable that is 1 if the fleet is able to achieve the change in SoC in the allotted time and 0 if it is unable to do so because it encounters one of its limits. This method can be used with dynamic programming to optimize a SoC/power schedule over a finite time horizon.

D.6.2 Coordination Scheme

When real and reactive power requests are sent to a fleet of two or more devices, the power request must be split between the devices such that the request is met without exceeding any of the device's limits. To accomplish this task, the battery-inverter fleet model divides the total request by the number of devices in the fleet and sends the scaled request to all available devices. Under certain conditions, some of the devices in a fleet may not be able to supply the full amount of power requested of them. When this happens, the algorithm designates these devices as `not available,' and then divides the total power shortfall equally among the remaining `available' devices. This process continues until either the power request is met to within a threshold or all of the devices are `not available.' This process works the same for both active and reactive power. Figure D.5 shows a flow chart for this algorithm.

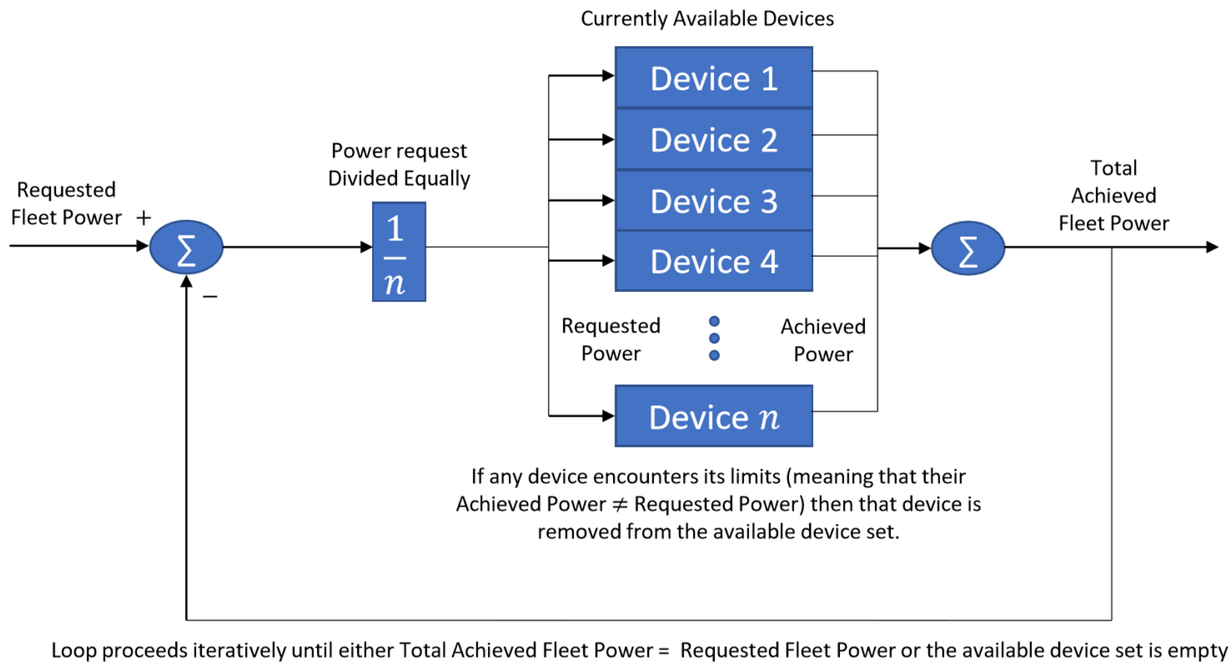

Figure D.5. Fleet response recursive implementation diagram.

D.6.3 Model Validation and Example Usage

The ERM and CRM discussed above were validated by simulating 30 devices with real test data, shown in Figure D.6 for the ERM (top) and CRM (bottom), and comparing their SoC trajectories to the SoC trajectory reported by the battery management system of the device under test. A standard normal distribution is used in this example to randomly initialize the SoC of each device in the simulated fleets. This simulation test performs three tasks. First, it demonstrates that both models produce results that closely follow the actual achieved performance of a real battery-inverter system. Second, it demonstrates what happens when some of the devices in the fleet encounter their low SoC limits. In this case the burden of supplying the requested power falls on the remaining available units as described above. Third, it demonstrates the difference between the models in that the CRM fleet ends up curtailing power near the end of the test, whereas the ERM-based fleet does not. While potentially more accurate, the CRM takes considerably longer to simulate the test and hence may not be computationally efficient enough for very large power system simulations involving hundreds or thousands of batteries.

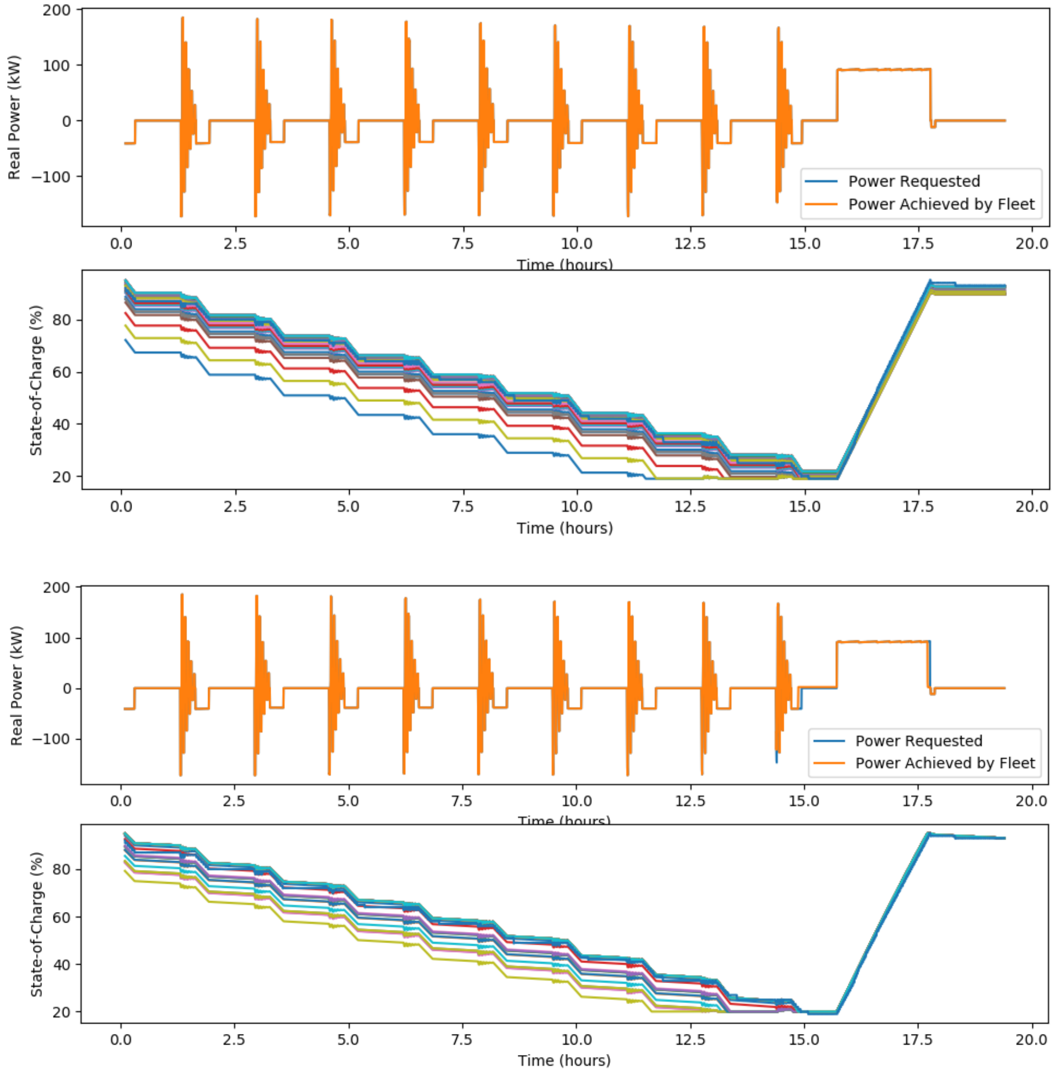

Figure D.6. Fleet Model Validation Simulation Test results of 30 battery-inverter devices using the ERM model (top) and CRM model (bottom).

D.7 References

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Appendix E – Fuel Cells

E.1 Basic Device Purpose

A hydrogen fuel cell is an energy device that converts chemicals to electrical energy by using a chemical reaction between an oxidant (oxygen, ambient air, or another oxidizing agent) and a fuel (hydrogen) that are deployed on electrodes. The basic element of a fuel cell is a unit cell (Figure E.1.). Hydrogen is disassociated at the anode catalytic layer into positively charged hydrogen ions and electrons. The hydrogen ions drift through the electrolyte to the cathode, where the electrolyte prohibits electrons from passing through. Electrons complete the path of an electrical circuit by flowing from the anode, through an electrical load to the cathode. Electrons, hydrogen ions, and oxygen recombine at the cathode catalytic layer and form water.

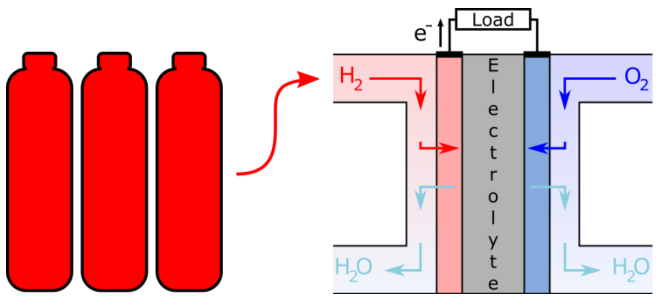

Figure E.1. Unit cell – principle of operation.

Different fuel cell technologies that are commercially available include the following:

- proton exchange membrane fuel cell (PEMFC/PEM Fuel Cell)
- alkaline fuel cell (AFC)
- phosphoric acid fuel cell (PAFC)
- molten carbonite fuel cell (MCFC)
- solid oxide fuel cell (SOFC)
- direct methanol fuel cell.

Each technology has different properties, making it relatively more or less suitable for certain applications. In this device model no particular fuel cell technology will be emphasized, considering that all can be characterized for providing the grid services using the same general principle. That is, a chemical process between hydrogen and an oxidant (e.g., oxygen) results in the generation of electricity, heat, and water. By varying the device's operating point (generated electrical energy), the device can increase or decrease its power generation, thus providing grid service.

E.2 Standard Controls and Normal Operational Modes

Fuel cell control is usually embedded in a low-level controller (LLC) that is in charge of monitoring and synthetizing the required controls. The LLC monitors voltages, currents, temperatures, and pressures of the respective equipment and sets the control according to the implemented control algorithm. The normal operating modes of a fuel cell are defined as follows:

- OFF mode

- ON mode – Hydrogen is consumed to produce power

  The operating point is selected based on the required power output and the amount of stored hydrogen. If the fuel cell is interfaced to a high-level controller (such as a front-end controller), the optimization algorithm will include additional properties, e.g., electricity price, and based on these properties will optimize the fuel cell operation over a certain period of time.

- AUTO mode

  For a fuel cell to be eligible for performing in AUTO (stand-alone) operating mode, it has to be operated by a high-level control instance that will be making decisions about the current operating point and providing the input to the LLC, which in turn will be handling the required control values for that particular operating point.

E.2.1 Controller

The fuel cell is equipped with a LLC that monitors the operational state of the fuel cell and determines the values to achieve the required operating point. Monitored states can be:

- DC current (voltage) in the electrochemical cells
- pressures in hoses, high/medium pressure hydrogen tank(s)
- temperatures of the block, hose, tank.

Also, auxiliary devices such as a power electronics converter could be monitored and controlled by the LLC. These devices could be operated by its own dedicated controller, where the reference values would be set by the fuel cell's LLC.

In addition to the LLC, a high-level control could be interfaced to the LLC. This can be a remote agent (utility, aggregator, etc.), a front-end controller (FEC; Figure E.2.), or any other form of controller. If a remote agent is providing the high-level control, the LLC has to be capable of receiving and understanding the control requirement, as well as sending the decision and status back to the agent, which is usually parsed using OpenADR or OpenADR 2.0.

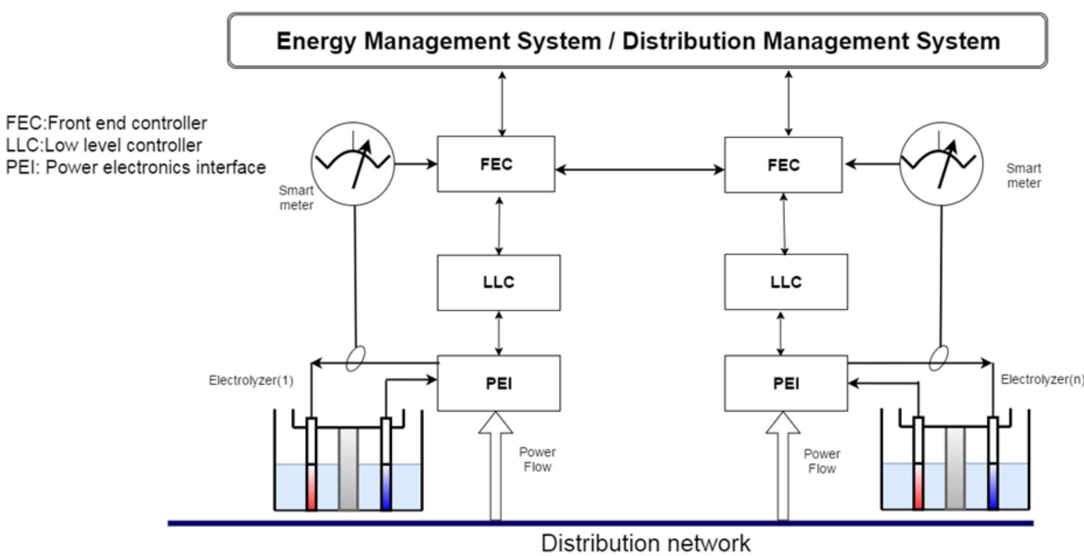

Figure E.2. Front-end controller system architecture.

E.2.2 Minimum Control Functionality – Response to Grid Signals

The minimum functionality of the controller with the respect to the grid signals shall be:

- turn the fuel cell ON
- turn the fuel cell OFF
- operating point HOLD
  - The operating point is defined as the lowest DC voltage/DC current (power), before the fuel cell turns OFF. Typically the power rating of this operating point is between 10% and 15% of the rated power.
    - Autonomous
      - In case the *device* is able to perform the autonomous response. It is typically managed by *separate controller*.

Minimum Control Functionality – Autonomous Response to Voltage and Frequency

Autonomous response to voltage and frequency deviations at the PCC of the device to the power grid is overlooked and controlled by *separate controller*.

To illustrate the operation, the control action is described for the case that front-end controller is the *separate controller*. For the sake of simplicity, only active power adjustment is observed. The overall principle applies for reactive power adjustment as well. The active power is here considered to remedy the voltage deviation by reducing the current and therefore reducing the voltage drop at the PCC. The following sequence is followed for frequency and/or voltage regulation through real power adjustment:

When frequency or voltage is <u>below</u> the threshold value:

- Sensors (e.g. Phasor Measurement Unit) provide frequency and/or voltage measurement values.
- Slow loop (frequency loop and/or voltage loop) calculates value of the *power value to be adjusted* (ΔP_f and/or ΔP_V) to counteract the disturbance. The calculation is carried out based on the frequency/voltage deviation, hydrogen level (pressure) in storage tanks, and control preset values which are selected by end-user. Further properties might be encompassed.
- Calculated change of *power adjustment* (ΔP_f and/orΔP_V) are passed to the *output selector*. The output selector observes the maintained operating point, takes into account the *power adjustment* values, and calculates the new operating point (power consumption value).
- The new operating point is communicated to the LLC.
- LLC sets the new operating point by readjusting the control parameters.
- The new operating point is maintained as long as this action has helped to improve the power quality at the PCC, or the pre-programmed bandwidth for the frequency and/or voltage support has been reached. Else, the new operating point will be set.

For the case that frequency or voltage is <u>above</u> the threshold value, the same process will repeat.

The grid services in autonomous mode will be provided as long as the preset boundary values by the user are not met, for example hydrogen level (pressure) in storage tank.

During the process of frequency and/or voltage stabilization, FEC of one fuel cell will be communicating with other FECs of the same type of *devices* (fuel cells). This will help the remedy action within the local grid to be more efficient, because larger capacity will be available for the grid service to be provided.

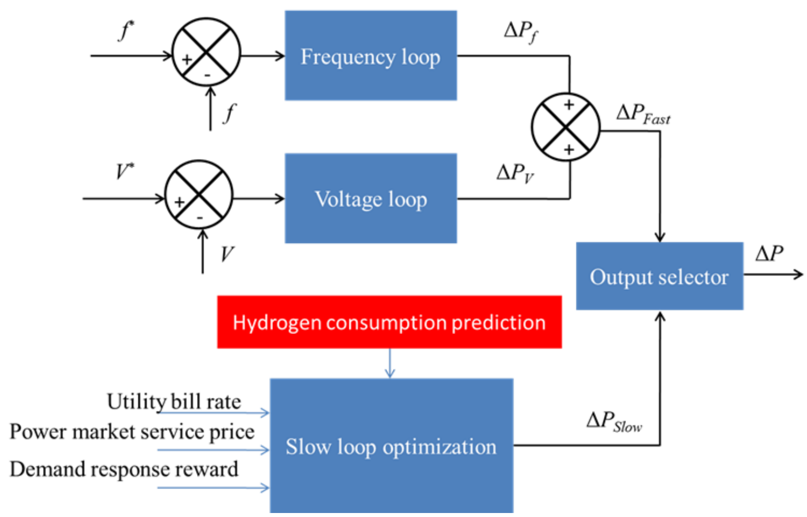

Figure E.3. Front-End Controller Control Flow Diagram.

E.3 Equipment Availability and Usage Patterns

Fuel cell are commonly used to power for transportation devices such as vehicles, motorcycles, and ships. Other applications include the power generation in remote places and cogeneration to provide heat and electricity to buildings and houses. The patter of usage will strongly depend on the specific application. For instance, the use of fuel cells to provide the electric power of a building will resemble the typical power demand curve, with a major energy requirement during noon and evening. It is worth noting that power generation from hydrogen fuel cells relies on the fuel availability or hydrogen stored

E.4 Change in Power Output Resulting from Response

Based on the value of operating point readjustment, i.e. power generation level, that has been calculated, low-level controller sets the new reference values for all control parameters. This leads to the power generation change – it will increase or decrease, depending on the *power adjustment* reference.

The actual change in operating point (power generation) will be handled through power electronics converter. The new reference will be translated into newly determined firing angles for power transistors, in order to achieve the new power generation. The remaining control parameters should also be adjusted, if required.

E.5 Device Model

E.5.1 Assumptions

Assumed parameters in the *Recommended Practice* are all temperatures, pressures, and hydrogen consumption rate that are required to be monitored and/or controlled, for *device* to operate and provide grid services. The *Recommended Practice* focuses on providing power grid service which is electrical and is quantified by changing the electrical power generation. The low-level controller will secure normal operation of the *device* and keep the abovementioned parameters within band defined by OEM.

Mathematical model assumptions

The mathematical model developed for a PEM fuel cell is based on the following assumptions:

- One dimensional analysis.
- Ideal and uniform distribution of gases.
- Constant pressure in the fuel cell gas flow channels.
- The parameters of each cell can be lumped together to represent the behavior of the entire stack.
- Both the fuel (hydrogen) and the oxidant (air) are humidified.
- The temperature is maintained homogeneous in the fuel cell by an external cooling system.
- The hydrogen is modeled as an ideal gas.
- The change in specific heats of hydrogen, air, and water with temperature are negligible.

E.5.2 Parameters/Equipment Characteristics

F: Faraday constant, $F = 96485.34\ C/mol$
R: universal constant of gases, $R = 8.31447 J/mol.K$
A: area of cells, $A = 200\ cm^2$
N_c: number of electrolyzer cells connected in series, $N_c = 20$
V_{tank}: tank volume, $V_{tank} = 0.3\ m^3$
$P_{max,t}$: maximum tank pressure, $P_{max,t} = 52.5\ MPa$

E.5.3 Variables

Variables considered in the mathematical model for the fuel cell:

V: operating voltage (V).
i: current density (A/cm^2).
P: power requirement for operation (W)
H_{2g}: hydrogen consumption rate (mol/s)
O_{2g}: oxygen consumption rate (mol/s)
T: operation temperature (°C or K).
ΔH^0: enthalpy (kj/mol)

ΔS^0: entropy (kj/mol-K)
ΔG^0: Gibbs free energy (kJ/mol), $\Delta G^0 = \Delta H^0 - T\Delta S^0$
N_c: number of cells connected in series
V_{tn}: thermoneutral voltage (V), $V_{tn} = \Delta H^0/nF$
V_r: reversible potential (V), $V_{rev} = \Delta G^0/nF$
V_{act}: activation loss (V)
V_{ohm}: ohmic loss (V)
V_{con}: concentration loss (V)
α_e: symmetry factor
i_0: exchange current density (A/cm^2)
i_L: limiting current density (A/cm^2)
η_F: Faraday efficiency.
$\dot{W}_c$: compressor power (W)
$\dot{m}_{H_{2g}}$: mass flow rate of produced H_{2g}, (kg/s)
c_p: specific heat of hydrogen at constant pressure (kj/kg-K)
c_v: specific heat of hydrogen at constant volume (kj/kg-K)
γ: specific heat ratio, $\gamma = c_p/c_v$
T_{out}: hydrogen temperature at compressor's exit (K)
T_{in}: hydrogen temperature at compressor's inlet (k)

E.5.4 Boundary Conditions

The boundary conditions considered in this model are as follows:

- The operating current in each cell is limited to between 0 A and 25 A.
- The operating voltage in each cell is limited to between 0 A and 1.21 V.
- The minimum SoC of the hydrogen storage tank is 20% of $P_{max,t}$.
- The maximum SoC of the hydrogen storage tank is 95% of $P_{max,t}$.

E.5.5 Physical Equations

Hydrogen flows through the PEM and diffuses to the catalyst layer. Hydrogen ionizes as H^+ and two electrons, i.e., as follows:

$$H_2 \longrightarrow 2H^+ + 2e^- \tag{E.1}$$

Oxygen diffuses in the cathode side and combines with hydrogen ions and electrons to form water according to the following reaction:

$$O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O \tag{E.2}$$

The overall reaction in the fuel cell is then

$$2H^+ + 2e^- + \frac{1}{2}O_2 \longrightarrow H_2O + electricity \tag{E.3}$$

The operation cell voltage in a single cell of the fuel cell can be expressed as follows (Benchouia et al. 2013):

$$V_c = V_r - V_{act} - V_{ohm} - V_{con} \tag{E.4}$$

The voltage of a full cell composed of N_c number of cells is then:

$$V = N_c V_c \tag{E.5}$$

The reversible voltage is $V_r = 1.229\ V$ at 25°C. It is defined as follows:

$$V_r = \frac{-\Delta G}{2F} \tag{E.6}$$

The activation loss can be determined from the Tafel Equation:

$$V_{act} = \frac{RT}{\alpha F} ln\left(\frac{i+i_n}{i_0}\right) \tag{E.7}$$

The ohmic loss, in terms of the total resistance (R_{tot}) in the fuel cell (electric and ionic resistance of the electrolyte) is given by (Peighambardoust et al. 2010; Dicks and Rand 2018):

$$V_{ohm} = (i + i_n)R_{tot} \tag{E.8}$$

The concentration loss or mass transport loss is determined from the following equation (Dicks and Rand 2018):

$$V_{con} = -\frac{RT}{2F} ln\left(1 - \frac{i+i_n}{i_L}\right) \tag{E.9}$$

In Equations (E.7) and (E.8), i_n is the sum of current density equivalent of fuel crossover and the internal current density (Dicks and Rand 2018).

An alternative way to determine concentration losses is by using the empirical equation [3]

$$V_{con} = a * exp(bi) \tag{E.10}$$

where a and b are constants determined experimentally.

Substituting Equations (E.7), (E.8), and (E.10) into Equation (E.4) yields

$$V_c = E_{cell} - \frac{RT}{\alpha F} ln\left(\frac{i+i_n}{i_0}\right) - (i + i_n)R_{tot} + \frac{RT}{2F} ln\left(1 - \frac{i+i_n}{i_L}\right) \tag{E.11}$$

Equation (E.11) represents the voltage of a single cell in the device as a function of the current density, taking into account irreversibilities.

The Nernst potential (E_{cell}) can be calculated from

$$E_{cell} = V_r + \frac{RT}{2F} ln\left[p^*_{H_2} * \left(p^*_{O_2}\right)^{0.5}\right] \tag{E.12}$$

In Equation (E.12), $p_{H_2}^*$ and $p_{O_2}^*$ are the effective partial pressure of H_2 and O_2, respectively. The fuel and oxidant delay can be considered using the following equation (Wang 2005):

$$E_{d,cell} = \lambda_e \left[i(t) - Conv\left(i(t), exp\left(-\frac{r}{\tau_e} \right) \right) \right] \quad \text{(E.13)}$$

From Equations (E.11) and (E.13), the cell voltage is calculated as follows:

$$V_{cr} = V_c - E_{d,cell} \quad \text{(E.14)}$$

Table E.1. Values used in the PEM fuel cell model (Dicks and Rand 2018).

Parameter	$\boldsymbol{\alpha}$	$\boldsymbol{a}$ $\boldsymbol{(V)}$	$\boldsymbol{b}$ $\boldsymbol{(mA\ cm^{-2})}$	$\boldsymbol{i_n}$ $\boldsymbol{(mA\ cm^{-2})}$	$\boldsymbol{i_0}$ $\boldsymbol{(mA\ cm^{-2})}$	$\boldsymbol{i_L}$ $\boldsymbol{(mA\ cm^{-2})}$	$\boldsymbol{R_{tot}}$ $\boldsymbol{(k\Omega cm^2)}$
Value	0.5	3x10-5	8x10-3	2.0	0.067	900.0	30x10-6

The hydrogen and oxygen consumption rate for a stochiometric reaction are determined as follows:

$$H_{2g} = 2O_{2g} = \frac{N_c I}{2F} \quad \text{(E.15)}$$

The energy efficiency of a fuel cell is defined as follows (Ulleberg 1998):

$$n_e = \frac{V}{V_{tn}} \quad \text{(E.16)}$$

The thermoneutral voltage is defined as $V_{tn} = \Delta H^0/2F$. For a temperature of 25°C, $V_{tn} = 1.48$ V. The effect of temperature on V_{tn} is very low. Then it can be considered independent of temperature Pascuzzi et al. 2018).

The fuel cell efficiency can be determined as the ratio between the energy output and the energy of the fuel, i.e., as follows:

$$n_{fc} = \frac{P_{out}}{H_{2g} LHV} \quad \text{(E.17)}$$

where the LHV for hydrogen is 241820 J/mol.

E.5.6 End-Use Load (if any)

The system of fuel cell will produce power using the stored hydrogen. The hydrogen consumption rate depends on the imposed load to be met, the power rate of each fuel cell, and the number of fuel cell stacks. The imposed power load corresponds to a downscaled profile of a 5-minute power demand in California for January 17, 2019 (CAISO2019). This curve captures the behavior of the real load profile such as maximum and minimum demand, variations, etc. This load profile is presented in Figure E.4.

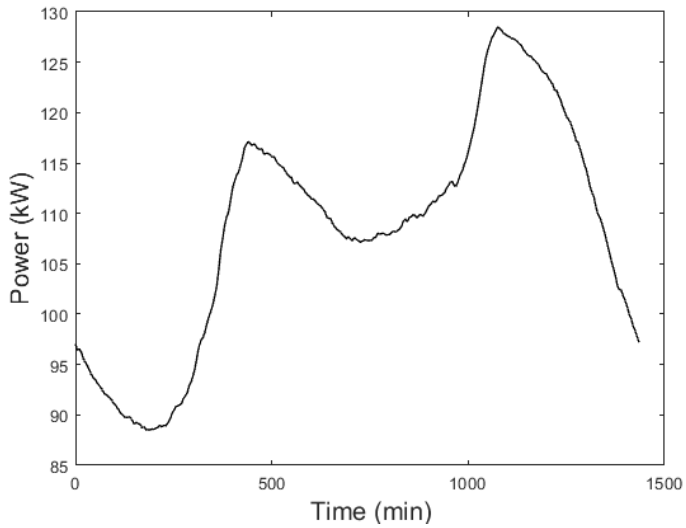

Figure E.4. Load profile used for the fuel cell model.

E.5.7 Parasitic Loads (if any)

The parasitic load for the fuel corresponds to the energy consumption of ancillary devices such as water pump during the fuel cell standby mode. These parasitic loads are not currently considered in the model because they are very low when compared with the fuel cell power.

E.5.8 Possible Device Responses

E.5.9 Constraints on Device Response

The fuel cell response is constrained to the SoC of hydrogen. In the model, the power generation requires at least a 20% of the maximum pressure in the storage tank(s). The other constraint for the device response is related to the power ramping time of the device, which is included in the model as a time delay. There are also constraints of the device to respond because of design limits such as the maximum power per fuel cell stack.

E.5.10 Translating Device Model to Battery-Equivalent Model Parameters

The fuel cell operates under a base load that allows it to produce electricity in a steady-state condition at a specific hydrogen consumption rate. When no power is requested from the grid, it is assumed in the model that the hydrogen consumption and hydrogen production are the same, which results in a constant SoC.

If Grid Service Request = 0, the hydrogen consumption rate equals the hydrogen production rate:

$$P_{fuel\ cell} = P_{base\ load}. \tag{E.18}$$

The SoC is determined as follows:

$$SoC_i = SoC_{i+1} = constant \tag{E.19}$$

While Grid Service Request ≠ 0, the system of fuel cells will increase the hydrogen consumption to produce additional power in order to follow the imposed load. The hydrogen is depleted from the storage tank(s) and the SoC would decrease until it reaches a value of 20% of the maximum pressure (0.20 p_{max}) in the storage tank(s). The change in SoC (ΔSoC) is measured with respect to the previous constant SoC when no grid service was requested. In this case:

$$\Delta SoC = SoC_i - SoC_{i+1} \tag{E.20}$$

The current state of charge SoC_{i+1} is determined as follows:

$$SoC_{i+1} = SoC_i - \frac{(H_{2g}t)(RT/V_{tank})}{p_{max}} \tag{E.21}$$

where t, R, T, and V_{tank} are respectively the time, universal gas constant, temperature (in K) and tank or tanks volume.

The parameter-to-parameter translation of the fuel cell and the Battery-Equivalent Model is presented in the following table.

Table E.2. Translation of fuel cell parameters to Battery-Equivalent Model parameters.

Parameter	Fuel Cell Model	Battery-Equivalent Model
Power	Operating voltage (V) Operating current (I)	Output power P_{in}
Storage capacity	Tank(s) capacity (p_{max})	Maximum State of Charge SoC_{max}
Energy stored	Pressure in the storage tank(s)	Current state of charge SoC_{actual}
Operation time	continuous	Only if grid service is requested
Efficiency	Fuel cell efficiency (η_e)	$\eta = \frac{Power\ output * t}{H_{2g} * LHV_{H_2} * t}$

E.5.11 Device Impact Metrics

None

E.5.11.1 Energy Impact Metrics

None

E.5.11.2 Amenity Impacts Metrics

None

E.5.11.3 Equipment Impacts Metrics

None

E.6 Device Fleet

E.6.1 Default Fleet Characteristics (Instantiation)

Here we introduce the *FuelCellFleet* class and explain its methods. The illustration in Figure E.5 shows the full list of available methods. The *GridInfo* class can be used to create the power curve time-series data in the correct format. The *FuelCellFleet* class uses the *GridInfo* object to utilize the power curve data. The '__init__' method opens the config.ini file to extract the device model parameters as described in Section E.5.3. The *FuelCellFleet* once constructed, accepts the fleet request using the *process_request* method. The *process_request* method will keep track of the process variables such as the state of SoC and time-delta by calling the run method. The run method computes the power consumed along with the new state of SoC and outputs the fleet response.

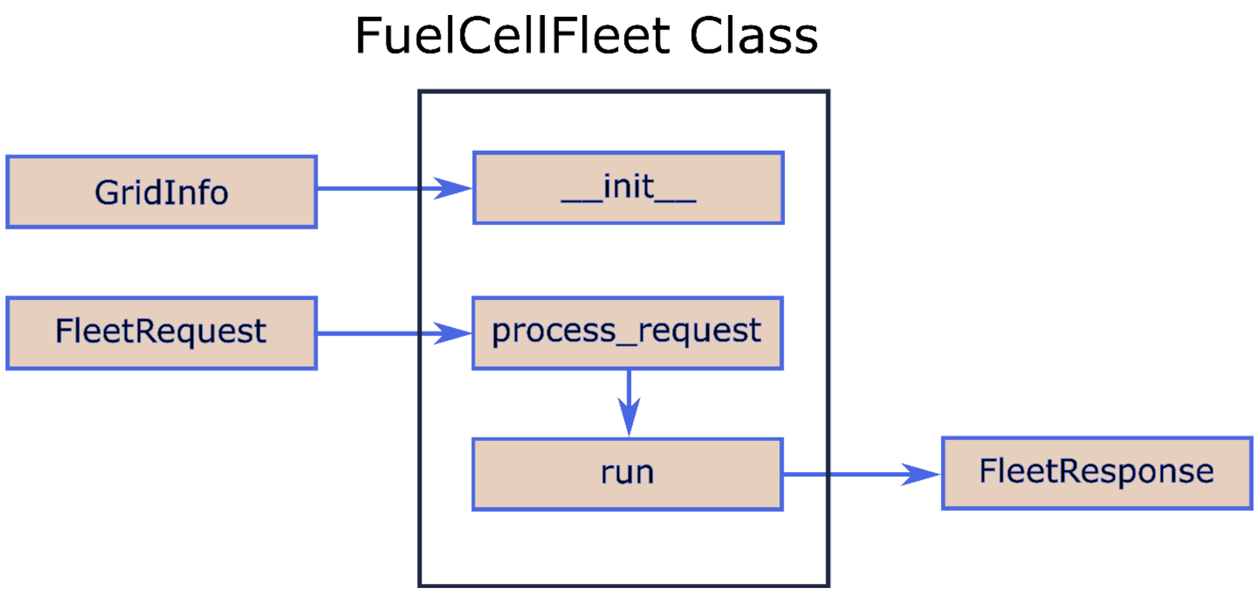

Figure E.5. FuelCellFleet Class method diagram

E.6.2 Coordination Scheme

Once the number of tanks and number of FuelCells in the fleet has been determined, the total grid service request is uniformly divided among all the available fuel cells and they provide their service. During a given timestep, if any fuel cell in the fleet when providing grid support reaches is SoC minimum or maximum limits, it will cease to provide grid support and will maintain its SoC for the remainder of its operation.

E.6.3 Example of Usage

The PEM fuel cell system used the stored hydrogen to produce electricity. The stored hydrogen becomes a source of energy available for power generation in fuel cells that perform grid services.

The hydrogen consumption rate (mol/s) under grid service conditions is displayed in Figure E.6. As expected, the power generation is proportional to the hydrogen consumption. The transient behavior of current and voltage to supply an imposed power demand is presented in Figure E.7. The fuel cell efficiency displayed in Figure E.8, shows a slight variation under transient operation.

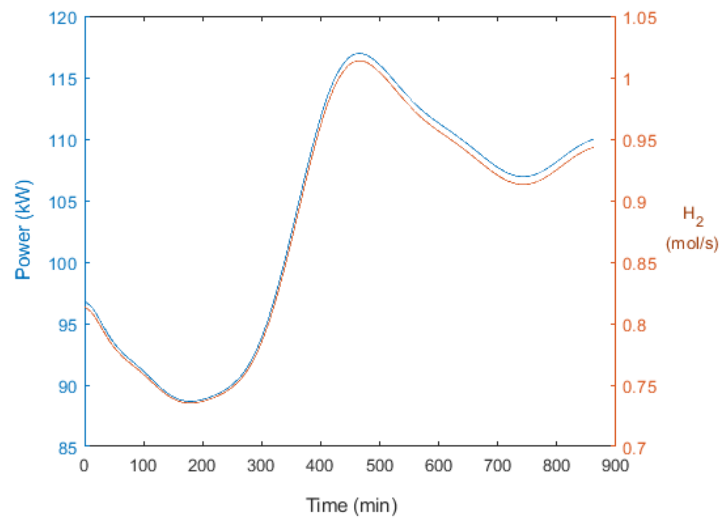

Figure E.6. Hydrogen consumption rate and power generation.

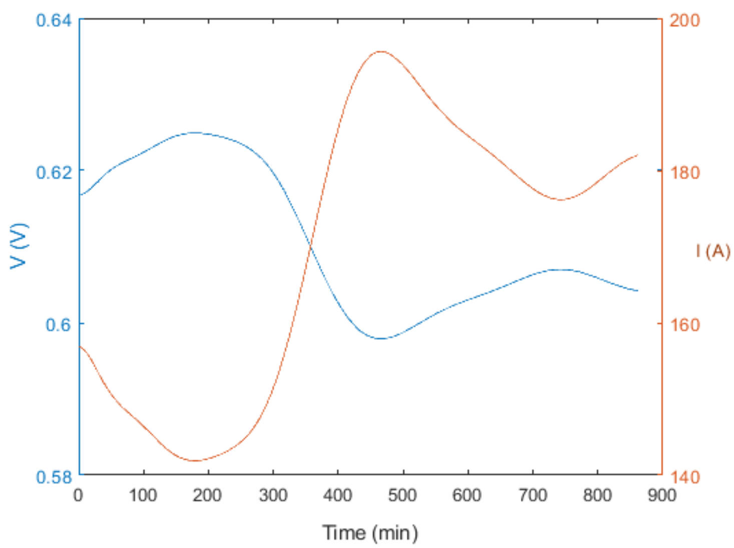

Figure E.7. Voltage and current variation.

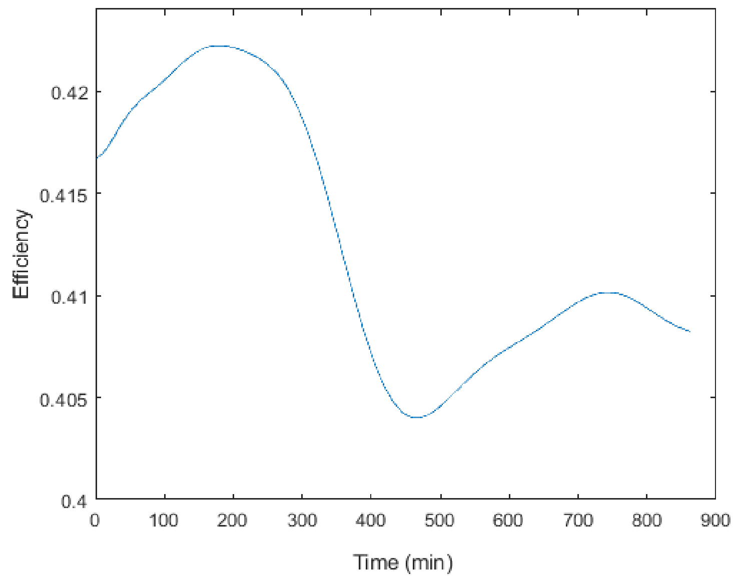

Figure E.8. Fuel cell efficiency

E.7 References

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Appendix F – Electrolyzers

F.1 Basic Device Purpose

A water electrolyzer is an energy device that performs an electrochemical process of splitting water molecules into oxygen and hydrogen. Direct current is passed through two electrodes located in a water tank, thereby producing oxygen at the anode (positive electrode) and hydrogen at the cathode (negative electrode). The basic element of an electrolyzer is an electrochemical cell (**Error! Reference source not found.**). The hydrogen is acquired at the cathodes and stored in hydrogen tanks (**Error! Reference source not found.**).

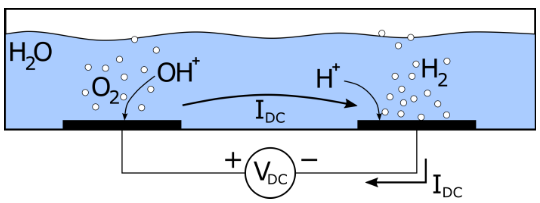


Figure F.1. Electrochemical cell – principle of operation.

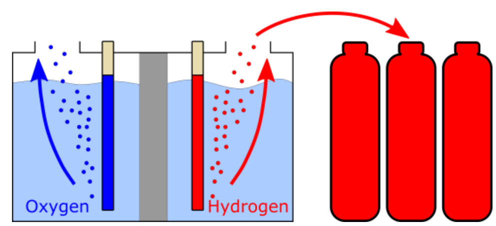


Figure F.2. Hydrogen storing.

While producing hydrogen, the electrolyzer consumes electrical energy. By varying the device's operating point (consumed electrical energy), the device can increase or decrease the power consumption, thus providing grid services.

F.2 Standard Controls and Normal Operational Modes

The electrolyzer control is usually embedded in a low-level controller (LLC) that monitors the operation and physical parameters, and synthetizes the reference control parameters. The LLC monitors voltages, currents, temperatures, and pressures of the *device* and adjusts the voltage (power consumption) and pressures according to the implemented control algorithm. The normal operating modes of the electrolyzer are defined as follows:

- Off mode – electrolyzer turned off.
- On mode – hydrogen generation mode.
  - The operating point is selected based on the hydrogen generation requirement (reference operating mode or set of modes provided by the user or automatically synthetized by the LLC) and hydrogen storage level. In case the *device* is interfaced to a high-level controller such as front-end controller (FEC), i.e., a *separate controller*, the operating point of the *device* will be set based on the implemented optimization algorithm.
- Autonomous mode
  - For the *device* to be eligible for operating in autonomous mode, it has to be interfaced to the *separate controller* (e.g., FEC) that will monitor additional parameters, other than physical, and apply the implemented optimization algorithm that will calculate the operating point of the *device*.

F.3 Equipment Availability and Usage Patterns

Electrolyzers are commonly used to produce hydrogen for further applications, including power generation through fuel cells. They are commonly hybridized with renewable energy technologies such as solar photovoltaic (PV) panels. The surplus generation during high solar radiation hours is used to produce hydrogen and store it in tanks. The stored energy in the form of compressed hydrogen can be extracted in full cells to provide power when solar radiation is not enough or during nighttime. For grid integration, electrolyzers can produce hydrogen at high peak generation. The energy stored can be added to the grid in high demand times or low generation stages. As an energy store element, the electrolyzer can also provide grid stability when a fraction of power generation comes from intermittent energy sources.

The minimum communications and controls for responding to grid signal are presented below.

F.3.1 Controller

The electrolyzer is equipped with an LLC that monitors the operating state of the electrolyzer (physical parameters) and calculates the reference values for control parameters, to achieve the required operating point and provide the electrolyzer's primary function. Monitored physical parameters can be

- direct current (DC) (voltage) in the electrolyzer, and/or electrochemical cells
- alternating current (AC) and DC voltages and/or currents in AC-DC and DC-DC power electronics converters
- pressures in hoses, high/medium pressure hydrogen tank(s), compressor inlet and outlet, etc.
- temperatures of the cooling block, hose, tank, etc.

Also, auxiliary devices such as power electronics converters and compressors could be monitored and controlled from the LLC, or the LLC could provide the control parameters for its own controllers. In case no *separate* controller is interfaced to the device, the *device's* LLC might be able to provide *signal-based respond* capability, i.e., to receive and understand the control requirement provided by high-level control, such as the Energy Management System, as well as to provide the control decision and operation status back, which is usually parsed using OpenADR or OpenADR 2.0.

If a *separate controller* is interfaced to the LLC, the LLC has to be able to communicate with it, usually through a serial port or Ethernet (TCP/IP, UDP, ModBUS, DNP3, etc.)

The *separate controller* allows for autonomous mode operation and additional power grid services apart from the ON and OFF modes. The *separate controller* can be a remote agent (utility, aggregator, etc.), a FEC, or any other form of controller that performs this type of control.

As an example of a *separate controller*, the concept of the FEC is briefly introduced. An FEC is a nearby placed, universal auxiliary device that monitors the electrolyzer's operating point (power consumption), electricity price, grid state (voltages and frequency), and FEC also communicates to other devices' FECs. The optimization algorithm embedded in FEC calculates based on states of the above-mentioned parameters the electrolzyer's operating point in real-time, with the objective to maximize the revenue (Figure F.3). In addition, it allows for providing power grid services in autonomous or controlled mode, in case the FEC is provided with voltage and/or current waveforms at the point of common coupling (PCC) of the *device* (Figure F.4). If grid services are being economically valued, the FEC can take this into account during the optimization of the operating point. The bandwidth of the allowed power consumption adjustment to provide voltage and frequency support can be predetermined by the user.

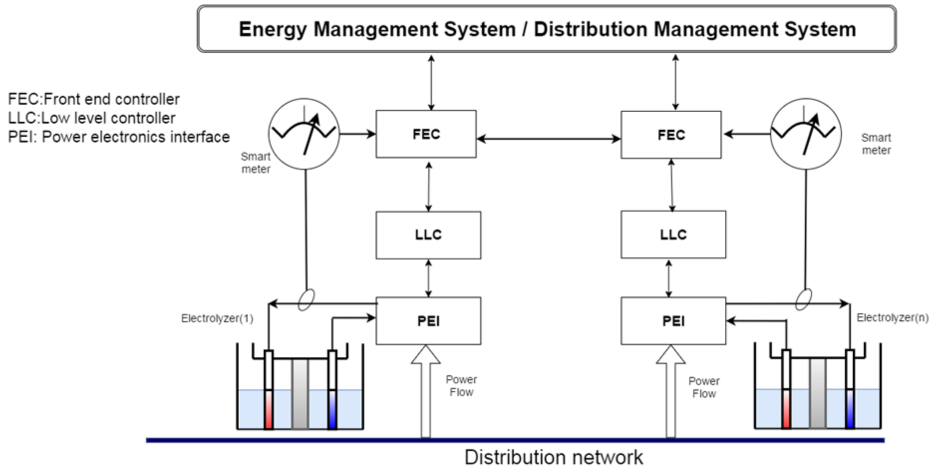


Figure F.3. Front-end controller system architecture.

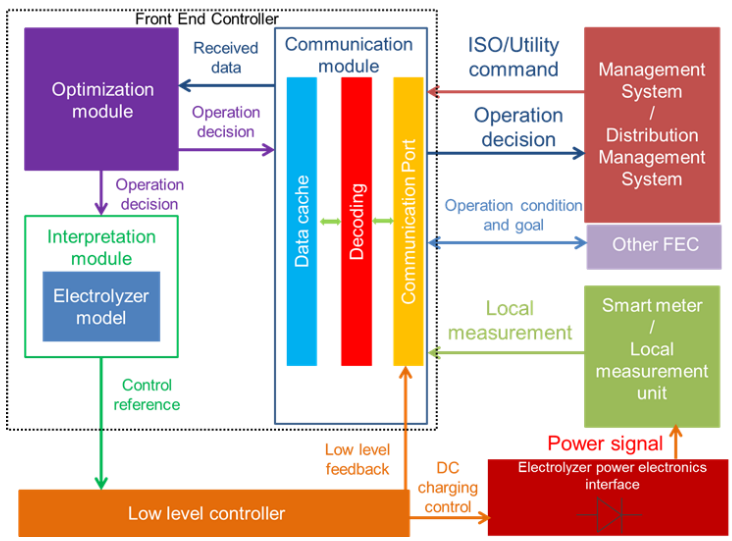


Figure F.4. Front-end controller control architecture.

The information flow is as follows: the FEC operating point setting is passed through to the LLC. The LLC receives the requested operating point, interrupts the present setting (if necessary), and adjusts the control parameters to achieve the requested operating point. The LLC monitors the states of the operating point, and reports the status back to the FEC.

F.3.2 Minimum Control Functionality – Response to Grid Signals

The minimum functionality of the *equipment* is defined here for an electrolyzer, controlled either solely by its LLC or in synergy with a *separate controller*. The minimum controllability as the response to grid signals should be as follows:

- Turn on

- Turn off
- Hold
  - The operating point is defined as the lowest power consumption, before the electrolyzer turns OFF (typically around 10% to 15% of the electrolyzer's rated power).
- Discrete (load step-change)
  - The *device* adjusts its real and/or reactive power consumption in discrete levels, by changing the volume of hydrogen generation.
- Auto
  - If the *device* is able to perform the autonomous response, it is typically managed by *separate controller*.

F.3.3 Minimum Control Functionality – Autonomous Response to Voltage and Frequency

Autonomous response to voltage and frequency deviations at the PCC of the device to the power grid is monitored and controlled by *separate controller*.

To illustrate the operation, the control action is described for the case that the FEC is the *separate controller,* see Fig F.5. For the sake of simplicity, only active power adjustment is observed. The overall principle applies for reactive power adjustment as well. Here, the active power is considered to remedy the voltage deviation by reducing the current and therefore reducing the voltage drop at the PCC. The following sequence is followed for frequency and/or voltage regulation through real power adjustment:

- When frequency or voltage is below the threshold value:
  - Sensors (e.g., Phasor Measurement Units) provide frequency and/or voltage measurement values.
  - The slow loop (frequency loop and/or voltage loop) calculates the value of the *power value to be adjusted* (ΔP_f and/or ΔP_V) to counteract the disturbance. The calculation is carried out based on the frequency/voltage deviation, hydrogen level (pressure) in storage tanks, and control preset values, which are selected by the end-user. Further properties might be encompassed.
  - The calculated changes in *power adjustment* (ΔP_f and/orΔP_V) are passed to the *output selector*. The output selector observes the maintained operating point, takes into account the *power adjustment* values, and calculates the new operating point (power consumption value).
  - The new operating point is communicated to the LLC.
  - The LLC sets the new operating point by readjusting the control parameters.
  - The new operating point is maintained as long as this action helps to improve the power quality at the PCC, or the pre-programmed bandwidth for the frequency and/or voltage support has been reached. Otherwise, a new operating point will be set.

If the frequency or voltage is above the threshold value, the same process will repeat.

The grid services in autonomous mode will be provided as long as the user's preset boundary values, for example the hydrogen level (pressure) in the storage tank, are not met.

During the process of frequency and/or voltage stabilization, the FEC of one electrolyzer will be communicating with other FECs of the same type of *devices* (electrolyzers). This will help the remedy action within the local grid to be more efficient, because larger capacity will be available for the grid service to be provided.

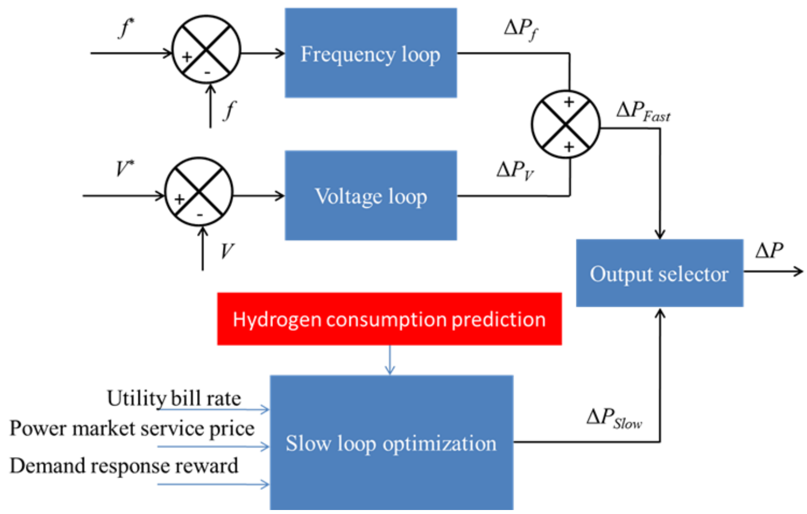


Figure F.5. Front-end controller control flow diagram.

F.4 Change in Power Output Resulting from Response

The mechanism for generating the *real and/or reactive power adjustment* is described in Sections F.3.2. and F.3.3. Based on the value of the operating point readjustment, i.e., power consumption level, that has been calculated, the LLC sets the new reference values for all control parameters. This leads to a power consumption change, which will increase or decrease depending on the *power adjustment* reference.

The actual change in operating point (power consumption of electrical energy) will be handled through power electronics converter. The new reference will be translated into newly determined firing angles for power transistors, in order to achieve the new power consumption. The remaining control parameters should also be adjusted, if required.

F.5 Assumed Parameters

Assumed parameters are all temperatures and pressures that are required to be monitored and/or controlled, for the *device* to operate and provide a grid services. The assumption is, that the LLC will secure normal operation of the *device* and keep the above-mentioned parameters within a band defined by the Original Equipment Manufacturer (OEM).

F.5.1 Eligibility Requirements

The device must be able to be interfaced with the test equipment, including the controllable power supplies, data acquisition equipment, communication equipment, etc. The characteristics and parameter values not mentioned before should be followed according to the recommended values provided by OEM.

Certain parameters play an important role for the *device* during grid service operation. These parameters can be categorized as follows:

- End-user limits: the electrolyzer might not be fully used to provide a grid service due to a hydrogen level (pressure) in the storage tanks, expected or actual demand for hydrogen to be generated, etc.
- Time limits: if hydrogen storage tanks are fully or mostly loaded, the *device* cannot provide grid service. Similarly, if the tanks are near or fully empty and the device is expected to curtail power consumption, and the hydrogen demand at the market is high, the *device* will most probably operate. To resolve this issue, grid service incentives must be considered.
- Equipment limits: power rating of the *device* is one of the factors that limits the *power adjustment value*. Hydrogen tank size limits the duration of the service (energy that is required or able to be deployed). While providing grid service over a longer time period, temperatures and/or pressures might increase, which will result in service termination.

F.5.2 Parameters to Be Characterized

The following parameters should be characterized:

- Maximum and minimum power consumption of the *device* – An operating point with minimum power consumption refers to the operating point with minimum DC voltage in electrochemical cells, below which the electrochemical process of electrolysis in the *device* is not feasible and the *device* shuts down.
- Change in power consumption of the *device* (on the AC side of the power converter).
- *Equipment time lag* – the time lag between the time instant when the reference is set and the time instant when the *device* begins to change its power consumption at the power converter at the PCC.
- *Separate controller time lag* – the time lag in controls, elapsed from the instant when the *separate controller* sends the control signal to the time instant when the LLC receives the signal.
- *Time to full response* – the time elapsed from the instant when the control to change the operating point is sent, to the instant when the *device* reaches the new operating point.
- *Ramp rate (ramp-up and ramp-down)* – the rate of change of the *device* real (and/or reactive) power consumption or output.
- *Response duration* – the duration of providing a grid service.
- *Energy storage capacity* – the mass (or moles) of generated hydrogen that can be stored in the storage tank(s).

- *Charging efficiency* – the efficiency of the *device* (electrolyzer) to convert electrical energy drawn from the grid at the PCC into chemical energy of generated hydrogen stored in tank(s).

F.6 Device Model

F.6.1 Assumptions

The assumed parameters, eligibility requirements, and parameters to be characterized for the electrolyzer are presented in section F5. The specific assumptions for the device model are presented in this section.

The mathematical model developed for a PEM electrolyzer is based on the following assumptions:

- One dimensional approach.
- Ideal and uniform distribution of gases.
- Constant pressure in the electrolyzer gas flow channel.
- The parameters of each cell can be lumped together to represent the behavior of the entire stack.
- The temperature is maintained homogeneous in the electrolyzer by an external cooling system.
- The hydrogen is modeled as an ideal gas.
- The change in specific heats of hydrogen with temperature are negligible.
- Power to move the feed water in the electrolyzer can be neglected because it is very low compared to the power to run the compressor.

F.6.2 Physical Equations

The reaction to split the liquid water into oxygen and hydrogen is expressed as follows:

$$2H_2O(l) \longrightarrow 2H_2(g) + \frac{1}{2}O_2(g) \tag{F.1}$$

The respective anode and cathode reactions are as follows:

$$H_2O(l) \longrightarrow \frac{1}{2}O_2(g) + 2H^+ + 2e^- \tag{F.2}$$

$$2H^+ + 2e^- \longrightarrow H_2(g) \tag{F.3}$$

The relationship between the electrode current and the potential for the reaction is given by the Butler-Volmer equation (Olivier et al. 2017):

$$I = I_0\left\{exp\left[\frac{(1-\alpha_e)n_eF}{RT}\left(V - V_{eq}\right)\right] - exp\left[-\frac{\alpha_e n_e F}{RT}\left(V - V_{eq}\right)\right]\right\} \tag{F.4}$$

Another empirical equation describing the relation between voltage and current is presented in Equation (F.5) (Ulleberg 1998):

$$V = V_{rev} + \frac{r_1 + r_2 T}{A_e} I + (s_1 + s_2 T + s_3 T^3) log\left(\frac{t_1 + t_2/T + \frac{t_3}{T^2}}{A_e} I + 1\right) \tag{F.5}$$

where r_i are coefficients for ohmic resistance of electrolyte and s_i and t_i are parameters for overvoltage on electrodes, respectively. These parameters can be obtained from experimental data. The values used in the model are presented in Table F.1.

Table F.1. Values for the coefficients $\boldsymbol{r_i}$, $\boldsymbol{s_i}$ and $\boldsymbol{t_i}$ used in the electrolyzer model.

$r_1 = 7.331e-5\ (\Omega m^2)$	$s_1 = 1.586e-1\ V$	$t_1 = 1.599e-2\ m^2A^{-1}$
$r_2 = -1.107e-7\ (\Omega m^2 {}^\circ C^{-1})$	$s_2 = 1.378e-3\ V^\circ C^{-1}$	$t_2 = -1.302\ m^2A^{-1}{}^\circ C$
$r_3 = 0$	$s_3 = -1.606e-5\ V^\circ C^{-2}$	$t_3 = 4.213e2\ m^2A^{-1}{}^\circ C^2$

The parameters presented in Table F.2 can be determined using experimental results following a systematic procedure for the best curve fitting (Ulleberg 1998; Khater et al. 2011).

The maximum and the actual hydrogen produced in the fuel cell are related through the Faraday efficiency, which is defined by (Castañeda et al. 2013):

$$\eta_F = 96.5\ exp\left(\frac{0.09}{I} - \frac{75.5}{I^2}\right). \tag{F.6}$$

This efficiency can also be found using the following empirical correlation (Ulleberg 1998):

$$\eta_F = a_1 exp\left(\frac{a_2 + a_3 T + a_4 T^2}{I/A} + \frac{a_5 + a_6 T + a_7 T^2}{(I/A)^2}\right) \tag{F.7}$$

Table F.2. Values for the coefficients $\boldsymbol{a_2}$ (Ulleberg 1998)

$a_1 = 0.995$	$a_2 = -9.5788\ m^{-2}A$	$a_3 = -0.0555 m^{-2}A^\circ C^{-1}$	$a_4 = 0$
$a_5 = 1502.7083\ m^{-4}A^2$	$a_6 = -70.8005\ m^{-4}A^{2\circ}C^{-1}$	$a_7 = 0$	

The hydrogen production flow rate (mol//h) can be calculated by:

$$H_{2g} = \frac{N_c I}{2F} \eta_F \tag{F.8}$$

An alternative relation for determining H_{2g} in Nm^3/h is to consider the ideal gas molar volume of 22.414x10^{-3} m^3/molar under standard conditions (Li at al. 2009); in this case,

$$H_{2g} = 80.69 \frac{N_c I}{2F} \eta_F \tag{F.9}$$

The voltage efficiency, also call energy efficiency, of the electrolyze is given by (Larminie and Dicks 2003)

$$\eta_V = \frac{V_{tn}}{V} \tag{F.10}$$

The power required for the electrolyzer stack is computed from

$$P = N_C VI \tag{F.11}$$

The hydrogen produced is routed through a compressor and then stored in a tank. The power consumption for the compressor can be expressed as follows:

$$\dot{W}_c = \frac{\dot{m}_{H2g}}{\eta_c} c_p (T_{out} - T_{in}) \tag{F.12}$$

where the isentropic efficiency $\eta_c = 0.8$ (Saravanamuttoo et al. 2001), and $c_p = 14.31$ kj/kg-K under standard conditions.

Heat losses in the compressor are taken into account through η_c. Then, the temperatures and pressures at compressor's inlet and outlet are taken into account by

$$\frac{T_{out}}{T_{in}} = \left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} \tag{F.13}$$

with $\gamma = 1.41$ under standard conditions.

Replacing Equation (F.13) into Equation (F.12) the compression power yields:

$$\dot{W}_c = \frac{\dot{m}_{H2g}}{\eta_c} c_p T_{in} \left[\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]. \tag{F.14}$$

T_{in} is the compressor's inlet temperature or the temperature of hydrogen coming out of the electrolyzer.

F.6.3 Parameters/Equipment Characteristics

Parameters used in the mathematical model to describe the physical behavior of the electrolyzer:

F: Faraday constant, $F = 96485.34\ C/mol$
R universal constant of gases, $R = 8.31447 J/mol.K$
A: area of electrode, $A = 0.25\ m^2$
N_c: number of electrolyzer cells connected in series, $N_c = 12$
η_c: isentropic efficiency of the compressor, $\eta_c = 0.8$
V_{tank}: tank volume, $V_{tank} = 0.3\ m^3$ (MAHYTEC 2019)
$P_{max,t}$: maximum tank pressure, $P_{max,t} = 52.5\ MPa$.

F.6.4 Variables

Variables considered in the mathematical model for the electrolyzer:

V: operating voltage (V).
I: operating current (A).
P: power requirement for operation (W)

H_{2g}: hydrogen producing rate (mol/s)
T: operation temperature (°C or K).
ΔH^0: enthalpy (kj/mol)
ΔS^0: entropy (kj/mol-K)
ΔG^0: Gibbs free energy (kJ/mol), $\Delta G^0 = \Delta H^0 - T\Delta S^0$
N_c: number of electrolyzer cells connected in series
A: electrolyzer area (cm^2 or m^2)
V_{tn}: thermoneutral voltage (V), $V_{tn} = \Delta H^0/nF$
V_{rev}: reversible potential (V), $V_{rev} = \Delta G^0/nF$
α_e: symmetry factor
I_0: exchange current (A)
η_F: Faraday efficiency.
$\dot{W}_c$: compressor power (W)
$\dot{m}_{H_{2g}}$: mass flow rate of produced H_{2g}, (kg/s)
c_p: specific heat of hydrogen at constant pressure (kj/kg-K)
c_v: specific heat of hydrogen at constant volume (kj/kg-K)
γ: specific heat ratio, $\gamma = c_p/c_v$
T_{out}: hydrogen temperature at compressor's exit (K)
T_{in}: hydrogen temperature at compressor's inlet (k).

F.6.5 Boundary Conditions

The boundary conditions considered in this model are as follows:

- The minimum SoC of the hydrogen storage tank is 20% of $P_{max,t}$.
- The maximum SoC of the hydrogen storage tank is 95% of $P_{max,t}$.
- The minimum operation voltage is V_{tn} = 1.23V (minimum voltage for water electrolysis).

F.6.6 End-Use Load (if any)

The system of electrolyzers will produce hydrogen using the imposed load profile. In the electrolyzer model, the load corresponds to a downscaled profile of a 5-minute power demand in California for January 17, 2019 (CAISO 2019). This curve captures the behavior of the real load profile such as maximum and minimum demand, variations, etc. This load profile is presented in Figure F.6.

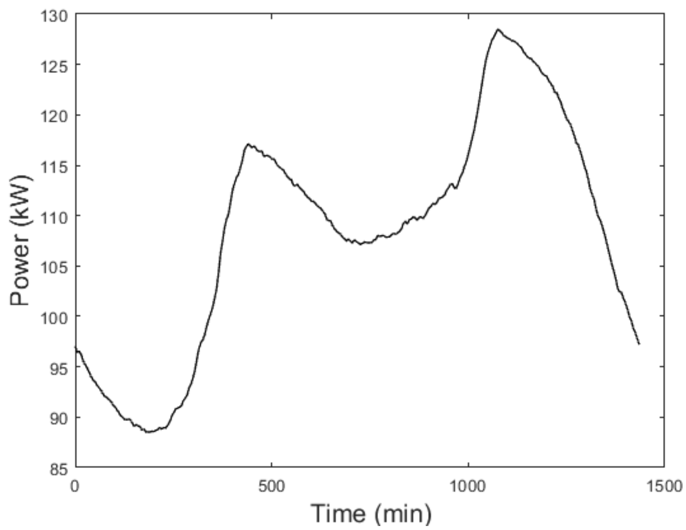


Figure F.6. Load profile used for the electrolyzer model.

F.6.7 Parasitic Loads (if any)

The Faradic efficiency is a way to assess the electrolysis system and it is defined as the ratio between the effective and theoretical maximum amount of hydrogen produced in the electrolyzer. It is often called current efficiency because it is linked to parasitic current losses along the gas ducts (Pascuzzi et al. 2016). Lower Faradic efficiencies are caused by an increase in temperature that produces less resistance and more parasitic current losses.

F.6.8 Possible Device Responses

F.6.9 Constraints on Device Response

The response of the electrolyzer is constrained to the SoC of hydrogen. The electrolyzer will start its operation only if the pressure in the tank(s) is lower than 95% of the maximum pressure. It will continue until the maximum SoC is reached. Other constraints for the electrolyzer under grid services are related to device design limits, such as the minimum required power or minimum voltage for water electrolysis.

F.6.10 Translating Device Model Parameters to Battery-Equivalent Model Parameters

The electrolyzer operates under a base load that allows it to produce hydrogen in a steady-state condition. In the model, it is assumed that the hydrogen production and consumption are the same when there is not grid service request. Under this condition, the SoC corresponding to the hydrogen content in the storage tank(s) remains constant.

If Grid Service Request = 0, the operating power (minimum power for water electrolysis) is calculated as follows:

$$P_{eletrolyzer} = P_{min} = P_{base\ load} \tag{F.15}$$

Then, the SoC remains constant, i.e.:

$$SoC_i = SoC_{i+1} = constant \tag{F.16}$$

which also means that the production and consumption hydrogen rates are the same.

While Grid Service Request ≠ 0, the stack of electrolyzers will increase the power consumption trying to follow the imposed load. The hydrogen production increases, thus SoC would increase until it reaches a value of 95% of the maximum pressure (0.95 p_{max}) in the storage tank(s). The change in SoC (ΔSoC) is measure respect to the previous constant SoC when no grid service was requested. In this case,

$$\Delta SoC = SoC_{i+1} - SoC_i \tag{F.17}$$

The current state of charge SoC_{i+1} is determined as follows:

$$SoC_{i+1} = SoC_i + \frac{(H_{2g}t)(RT/V_{tank})}{p_{max}} \tag{F.18}$$

where t, R, T, and V_{tank} are respectively the time, universal gas constant, temperature (in K) and tank or tanks volume.

The parameter-to-parameter translation of the electrolyzers and the Battery-Equivalent Model is presented in Table F.3

Table F.3. Translation of electrolyzer parameters to Battery-Equivalent Model parameters.

Parameter	Electrolyzer Model	Battery-Equivalent Model
Power	Operating voltage (V) Operating current (I)	Input power P_{in}
Storage capacity	Tank(s) capacity (p_{max})	Maximum state of charge SoC_{max}
Energy stored	Pressure in the storage tank(s)	Current state of charge SoC_{actual}
Operation time	continuous	Only if grid service is requested
Efficiency	Electrolyzer efficiency (η_e)	$\eta = \frac{Stored\ energy\ (H_2)}{Power\ supply * t}$

F.6.11 Device Impact Metrics

F.6.11.1 Energy Impact Metrics

A practical field application for electrolyzers is to study their impacts on absorbing the intermittency from renewable resources such as wind and solar energy. Extensive renewable energy penetration tests using electrolyzers were conducted by integrating a 225 kW rated electrolyzer stack located at the National Renewable Energy Laboratory with a distribution system modeled in Digital Real-Time Simulator running at Idaho National Laboratory. **Error! Reference source not found.** shows the electrolyzer response from 20% solar energy penetration in the power system. The hydrogen flow for one electrolyzer with the same solar penetration is shown in **Error! Reference source not found.**.

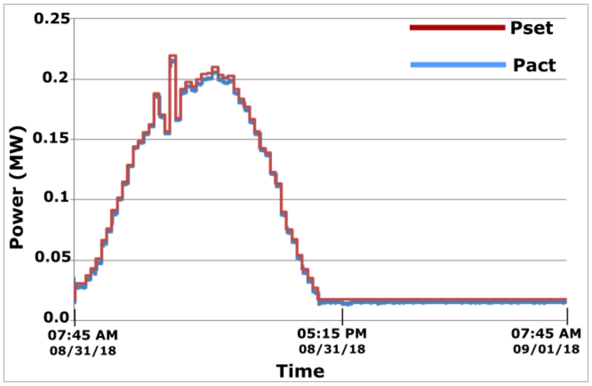


Figure F.7. Request and response with 20% renewable penetration for one electrolyzer distributed in the power system simulation.

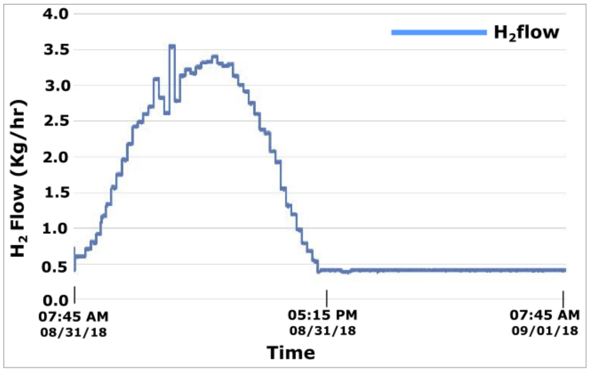


Figure F.8. Hydrogen flow for one electrolyzer.

F.6.11.2 Amenity Impacts Metrics

None

F.6.11.3 Equipment Impacts Metrics

None

F.7 Device Fleet

F.7.1 Default Fleet Characteristics (Instantiation)

Here we introduce the *ElectrolzyerFleet* class and explain its methods. The illustration in Figure 2 shows the full list of available methods. The *GridInfo* class can be used to create the power curve time-series data in the correct format. The *ElectrolzyerFleet* class uses the *GridInfo* object to utilize the power curve data. The '__init__' method opens the config.ini file to extract the device model parameters as described in Section F.6.3. The ElectrolyzerFleet once constructed, accepts the fleet request using the *process_request* method. The *process_request* method will keep track of the process variables such as the state of SoC and time-delta by calling the run method. The run method computes the H_2 produced along with the new state of SoC and outputs the fleet response.

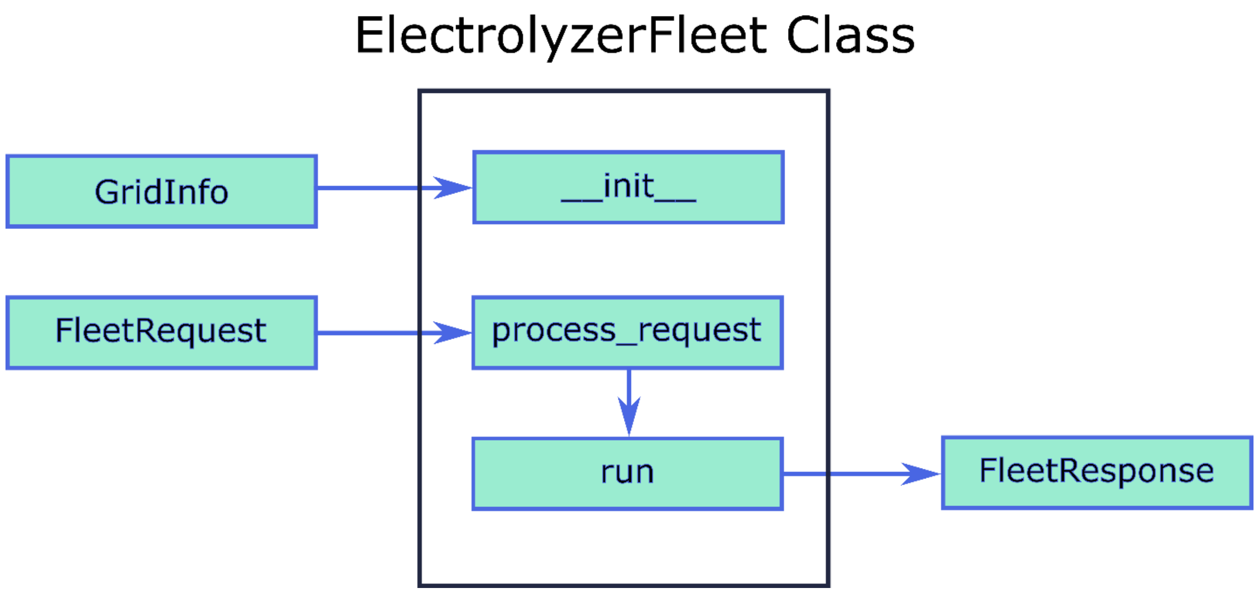


Figure F.9. ElectrolyzerFleet Class method diagram

F.7.2 Coordination Scheme

Once the number of tanks and number of electrolyzers in the fleet has been determined, the total grid service request is uniformly divided among all the available electrolyzers and they provide their service. During a given timestep, if any electrolyzer in the fleet when providing grid support reaches is SoC minimum or maximum limits, it will cease to provide grid support and will maintain its SoC for the remainder of its operation.

F.7.3 Example Usage

The electrolyzer system uses the energy from the grid to produce hydrogen. The stored hydrogen becomes an energy source of energy available for power generation in devices like fuel cells, which can also provide grid services. Then, the stored hydrogen can help to reduce the mismatch between generation and consumption characteristic of renewable energy sources.

The amount of hydrogen to be produced (mol/s) under grid service conditions is displayed in Figure F.10. As expected, the hydrogen production rate is proportional to the power supply. In particular, the current in the electrolyzer stack is the driving force for electrolysis. Because the electrolyzer is not a mechanical system involving a shaft rotation, inertia effects are small. The response time, which is less than 1 second, in this case is associated with a time delay due to mass transport of hydrogen ions across the membrane. The electrolyzer can operate dynamically under variable current and voltage as can be appreciated in Fig 11. However, this variation in power supply has a direct effect on the hydrogen production rate and voltage efficiency (see Fig. 12).

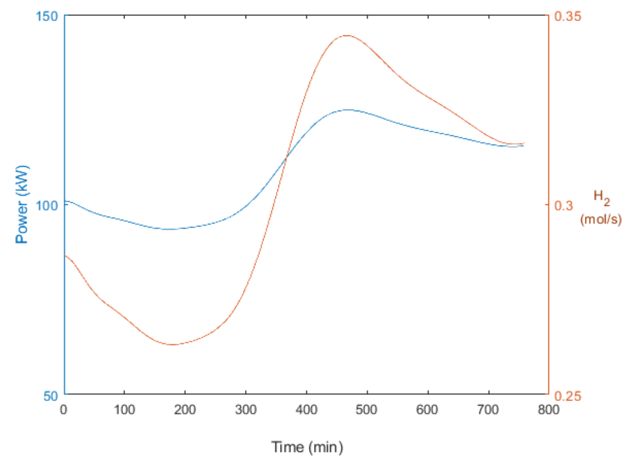
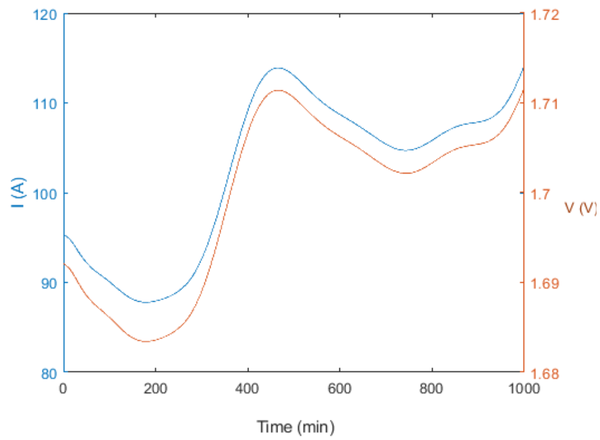


Figure F.10. Hydrogen production rate and power



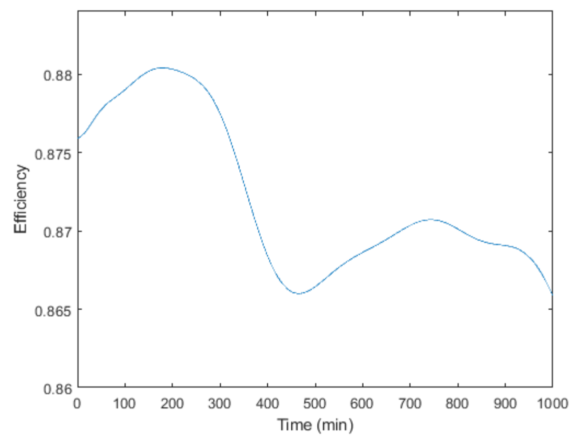


Figure F.11. Voltage and current variation.

Figure F.12. Voltage efficiency.

F.8 References

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Appendix G – Air Conditioners

G.1 Basic Device Purpose

The basic purpose of heating, ventilation, and air-conditioning (HVAC) systems is to maintain a building's indoor temperature between its current heating and cooling set points. Building thermal mass, including both building envelope and indoor thermal mass, allows HVAC units to be temporarily fully or partially shut down without immediate and substantial impact on the indoor thermal comfort. When shutting down units, the system must compensate for heat loss or gain through the building envelope, including air infiltration and ventilation. Because heat gain or loss this is primarily driven by the indoor-outdoor temperature difference, the load is a strong function of seasonal and diurnal outdoor temperatures, and the seasonal, diurnal, and day-of-week patterns of thermostat set points set by the occupants. In addition, the need for heating is reduced and the need for cooling is increased by internal heat gains from appliances, occupants, and solar loads. Internal heat gains vary strongly on a diurnal pattern and with some variation on a day-of-week basis. Similarly, solar heat gains vary strongly with the seasonal and hourly patterns of sun angles and the sky clearness index.

G.2 Standard Controls and Normal Operational Modes

The standard control for the HVAC units is the use of a thermostat for performing set point-based control of the units. The thermostat comprises of a temperature sensor, control logic, and relay circuity. For a given user set point temperature and an acceptable deadband, the thermostat turns on heating/cooling as the internal building temperature deviates from the set point.

Considering the control complexity of variable-speed systems, we focus on fixed-speed, single-stage systems here. In this initial test, we only address the on/off residential systems. We will extend this to variable-speed systems in our future work. Typical operational states are as follows:

- Standby – no active heating or cooling
- Active cooling – electricity consumed to cool the supply air
- Active heating – electricity consumed to heat the supply air.

G.3 Equipment Availability and Usage Patterns

Air conditioners are typically heavily used in summer and winter, and mildly used in shoulder seasons. Cooling and heating energy is stored in the building thermal mass, at indoor temperature set points controlled by the thermostat. Although more flexibility is available in summer and winter, it comes with the price of increased thermal losses for use of air conditioners as grid-connected devices. For example, in the summer cooling case, increased demand signal from the grid will drive the indoor temperature to be lower than that under normal operating conditions, which will introduce a larger temperature difference between indoor and outdoor temperatures.

G.4 Change in Power Output Resulting from Response

To meet the amount of power requested, air conditioners will make optimal decisions for deviations from original baseline operations without violating comfort and equipment hardware constraints:

- If the power requested is positive (power greater than the baseline case), an air conditioner will stop running if it is required to meet the request. The number of air conditioners that stop operating depends on the amount of power requested. This change in power output is constrained by the indoor comfort requirement, i.e., if an air conditioner must run before violating the temperature upper bound, it will start operating and the positive service requests will not be met.
- If the power requested is negative (power less than the baseline case), the air conditioner will start operation if it is required to meet the request. The number of air conditioners that start charging depends on the amount of power requested. This change in power output is constrained by the state of charge (SoC) of the air conditioner, i.e., when all the buildings are fully cooled (reach minimum temperature in the summer cooling case), negative service requests will not be met.

G.5 Device Model

G.5.1 Assumptions

One assumption for the building thermal model is that the available information is limited in terms of the number of measured points, e.g., only indoor temperature data measurements are available, and the general properties of building materials. In this work, we follow the classical resistance-capacitance (RC) model, also called lumped capacitance or network model, which is constituted with electrical analogue pattern with resistance (R) and capacitance (C). The effective heating and cooling gain coefficients—C_1, C_2 and C_3—are therefore introduced as one main innovation. C_1, C_2, and C_3 are used to adjust Q_{IHL}, Q_{AC}, and Q_{solar} for unknown factors. All C_1, C_2, and C_3 are assumed to be unknown and need to be identified.

In addition to the parameter assumptions listed above, the following additional assumptions are applied to the battery-equivalent air-conditioner model:

- No reactive power is modeled and the air conditioner cannot respond to any requests for grid services to provide reactive power.
- One hot summer month's disturbance profiles have been created and included with this model, during a longer run the profile will repeat it if needed. The start time and discretization time steps are set at the start of the fleet initialization.
- In addition to the minimum and maximum indoor temperatures imposed, a minimum SoC of 0.2 and maximum of 0.8 are imposed.
- The minimum capability to add or shed load depends on the instantaneous indoor and outdoor temperatures.

G.5.2 Parameters/Equipment Characteristics

Many of the assumed parameters for an individual air conditioner are determined at the start of the creation of the fleet. The assumed parameters and distributions are as follows:

- Air-conditioner set point temperature: The default air-conditioner set point is 23°C.
- Air-conditioner deadband: A deadband of 1°C is assumed for all air conditioners.

G.5.3 Boundary Conditions

The boundary conditions considered in this model are as follows:

- The minimum and maximum SoC of the Battery-Equivalent Model of an air conditioner are assumed to be 20 and 80%.
- Temperature: In the current model, changes in the rated power of the discharge/charge of the air conditioner are characterized with both indoor and outdoor temperatures (the coefficient of performance (COP) is represented by a polynomial).

G.5.4 Variables

Variables included in the air-conditioner model include the following:

- T_{amb} = ambient air temperature (in °C)
- $T_{deadband}$ = deadband temperature difference (in °C)
- Tsp = set point (ideal working temp in °C)
- Tin = indoor temperature (in °C)
- COP = coefficient of the HVAC system.

Characterization in the summer cooling case (Tsp ≤ Tmax):

- Occupants are allowed to turn off the HVAC system to tolerate the highest temperature, Tmax.
- Discharge: Tsp → Tmax.
- Charge: Tmax → Tsp.
- SOC(t) = $\frac{T_{max} - T_{in}}{T_{max} - T_{sp}}$.

Characterization in winter (Tsp ≥ Tmin)

- Occupants are allowed to turn off the HVAC system to tolerate the lowest temperature, Tmin.
- Discharge: Tsp → Tmin.
- Charge: Tmin → Tsp.
- SOC(t) = $\frac{T_{in} - T_{min}}{T_{sp} - T_{min}}$.

G.5.5 Physical Equations

An RC network model is used in this study, as shown in Figure G.1 to describe the thermal capacity of a building in an electrical analog pattern with resistance (R, m^{2}K/W) and capacity (C, J/(m^{2}K)). C_w, C_{attic}, C_{im}, and C_{in} are the equivalent overall thermal capacitances of exterior wall, air in attic, internal mass, and indoor air, respectively. R_w, R_{attic}, R_{roof}, R_{im}, and R_{win} are the equivalent overall thermal resistance of exterior walls, attic floor, roof, internal mass and external/exterior windows, respectively. All resistances and capacitances are assumed to be time invariant.

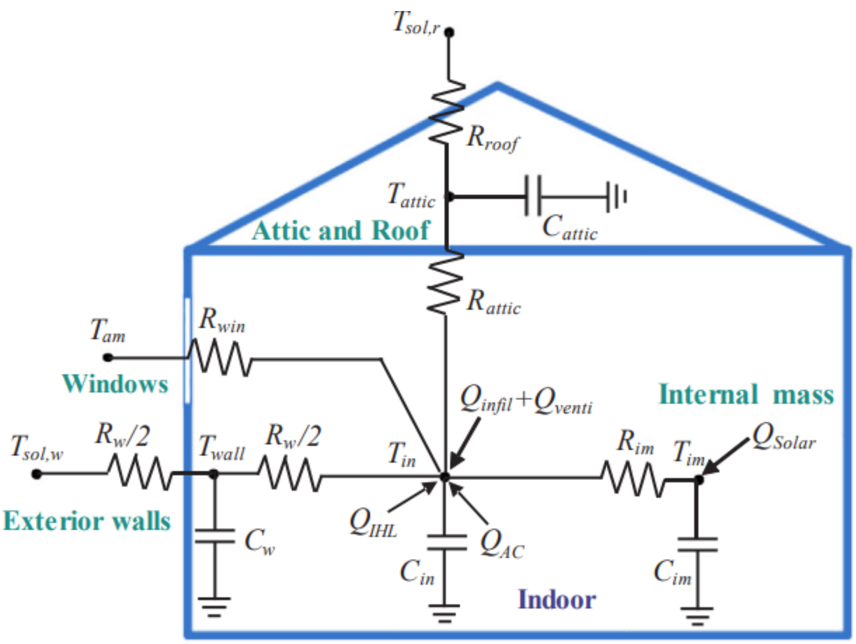

Figure G.1. Schematic of simplified building thermal network model (4R4C).[3]

[3] Cui B, Fan C, Munk J, Mao N, Xiao F, Dong J, Kuruganti T. A hybrid building thermal modeling approach for predicting temperatures in typical, detached, two-story houses. Appl Energy 2019; 236:101–16.

The RC model is described by the following differential equations, which represent the heat dynamic and energy balance in the building:

$$C_w \frac{dT_{wall}(t)}{dt} = \frac{T_{sol,w}(t) - T_{wall}(t)}{R_w/2} - \frac{T_{wall}(t) - T_{ave}(t)}{R_w/2} \quad \text{(G.1)}$$

$$C_{in} \frac{dT_{ave}(t)}{dt} = \frac{T_{wall}(t) - T_{ave}(t)}{R_w/2} + \frac{T_{attic}(t) - T_{ave}(t)}{R_{attic}} + \frac{T_{im}(t) - T_{ave}(t)}{R_{im}} + C_1 Q_{IHL,i} + C_2 Q_{AC,i} + C_3 Q_{solar,i} \quad \text{(G.2)}$$

$$C_{attic} \frac{dT_{attic}(t)}{dt} = \frac{T_{sol,r}(t) - T_{attic}(t)}{R_{roof}} - \frac{T_{attic}(t) - T_{ave}(t)}{R_{attic}} \quad \text{(G.3)}$$

$$C_{im} \frac{dT_{im}(t)}{dt} = -\frac{T_{im}(t) - T_{ave}(t)}{R_{im}} + C_1 Q_{IHL,m} + C_2 Q_{AC,m} + C_3 Q_{solar,m} \quad \text{(G.4)}$$

where, Q_{IHL} is sensible heat gains from indoor heat resources (W), e.g., human, equipment, and lighting, which is approximated by adding the sum of circuits, i.e., the total electrical energy use for each electrical circuit in the house, on each level for the separate floor.

Q_{AC} is the total cooling capacity (W) of the air conditioner as shown in the following equations, where W_{AC} is the power of the air-conditioning outdoor unit (W), and *COP* is the dynamic coefficient of performance, as shown in Equation (3.5), which is the product of rated COP and the COP adjustment function resulting from regression of the historic data for a single-speed system.

$$COP = 3.516(1.194 - 0.00589T_{out} - 0.0000411T_{out}^2) \quad \text{(G.5)}$$

T_{sol} is solar air temperature (°C), which is determined by the following equation:

$$T_{sol} = T_{out} + \frac{\alpha_{wall} \cdot I}{\alpha_{out}} \quad \text{(G.6)}$$

where

T_{out} = outdoor dry bulb temperature (°C),
I = the global solar radiation (W/m^2),
α_{wall} = the wall absorption coefficient, and
α_{out} = convective heat transfer coefficient of the envelope external surface (W/m^2·K).

It is worth noting that *R* and *C* reflect the physical characteristics of the building envelope and internal thermal mass; they are all assumed to be time invariant.

G.5.6 End-Use Load

This is the power consumed by the air-conditioning system to meet the quasi-steady-state loads of the conditioned space.

G.5.7 Parasitic Loads

Parasitic loads are not currently considered for HVAC systems because they contribute only a tiny portion of the total operating power. The control module that enables grid response may consume a few watts of standby power, but the amount varies depending on the specific hardware platform and is not simulated here.

G.5.8 Possible Device Responses

If any grid services are requested, the HVAC system will determine if it has the capability to provide grid services. The control logic for providing grid services depends on the type of service requested. If there is a request to increase load, certain HVAC units will be forced to switch on as long as the indoor temperature falls within the predefined comfort band and has the minimum required load-adding capacity. If there is a request to shed load, the HVAC unit will be forced off (if it would otherwise have been operating) as long as the indoor temperature falls within the predefined comfort band and has the minimum required load-shed capacity.

G.5.9 Constraints on Device Response

The main constraints on device response are listed above in terms of minimum and maximum allowed temperatures and SoC. A specific additional constraint is that there is a short-cycling constraint that prevents the HVAC unit from frequently switching ON and OFF. Moreover, to protect the lifespan of the device, there are a maximum number of grid services that the HVAC unit can provide in a certain time window. The maximum number of service calls that can be accepted is set by default to be infinite, but this number can be reduced if desired to model people eventually choosing to opt out of providing grid services due to dissatisfaction with the associated loss of comfort.

G.5.10 Device Model Validation

To validate the device model created here, we used the data collected from the reference building in different consecutive time periods under various operating conditions; e.g., different schedules of HVAC indoor temperature set points and different outdoor weather conditions are used for training and validating the RC model. The reference building being modeled in this research is a typical single-family detached house located in Knoxville, Tennessee. It was built in 2013 and is part of a large subdivision of similar homes built around the same time. The two-story, 223 m^2 (2,400 ft^2) physical and thermal properties consistent with the International Energy Conservation Code (IECC 2006). The data collected from 4/21/2017 to 5/16/2017 (25 consecutive days) are used for training and the data collected from 5/29/2017 to 6/14/2017 (17 consecutive days) are used for testing. When collecting data during this period, we fully excited the building system by enforcing a wide range of temperature set points for the thermostat. Hence, we tried to characterize all the possible dynamics under various working conditions. The scheduled air-conditioner and heater set points are listed in Table G.1. T_{act} is the measured overall mean indoor air temperature and TRC is the indoor temperature from the model for a 24-hour prediction horizon. The training results are shown in Figure G.2. The mean average error is around 0.5 C.

Table G.1. The scheduled AC and heater set points for RC model development (from Cui et al 2019).[1]

Day of the week	Time	Heater/AC set-points
Monday	8:00 am to 4:00 pm	18.3 °C/26.7 °C
	4:00 pm to 8:00 am	21.7 °C/24.4 °C
Tuesday	8:00 am to 5:00 pm	18.3 °C/26.7 °C
	5:00 pm to 8:00 am	20.6 °C/23.3 °C
Wednesday	8:00 am to 5:00 pm	18.3 °C/26.7 °C
	5:00 pm to 8:00 am	19.4 °C/25.6 °C
Thursday	8:00 am to 3:00 pm	19.4 °C/25.6 °C
	3:00 pm to 8:00 am	21.7 °C/24.4 °C
Friday	8:00 am to 6:00 pm	19.4 °C/25.6 °C
	6:00 pm to 8:00 am	20.6 °C/23.3 °C
Saturday	Whole day	20.6 °C/23.3 °C
Sunday	8:00 am to 10:00 pm	21.7 °C/24.4 °C
	10:00 pm to 8:00 am	20.6 °C/23.3 °C

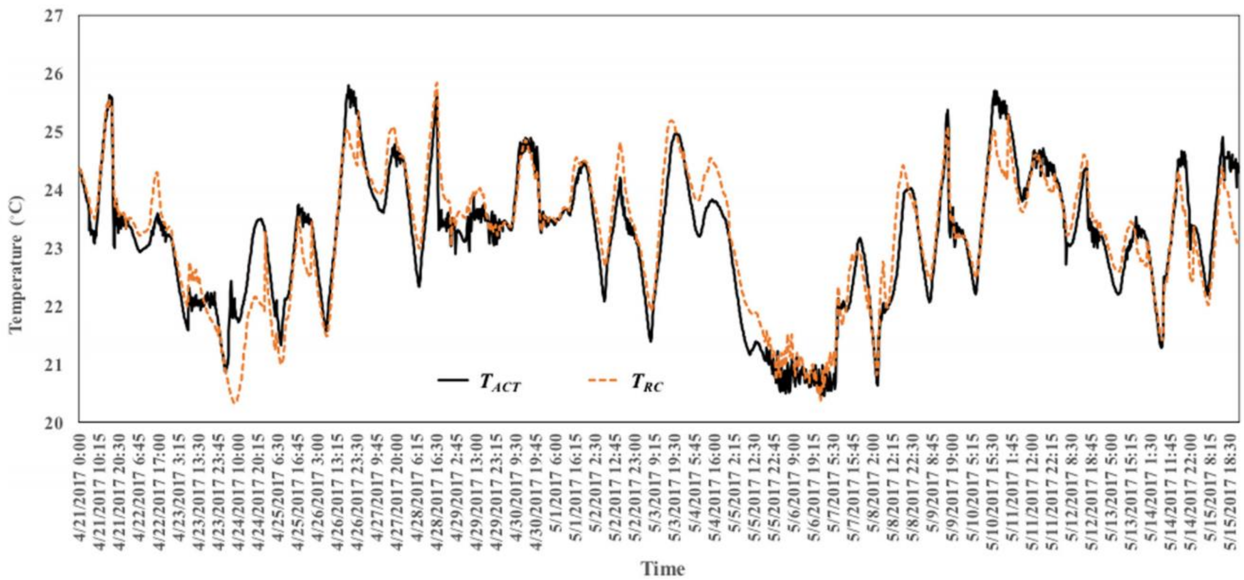

Figure G.2. RC model training results from April 21 to May 16, 2017 (from Cui et al. 2019).[1]

G.5.11 Translating Device Model to Battery-Equivalent Model Parameters

Now we start translating the above building thermal model into a battery equivalent model.

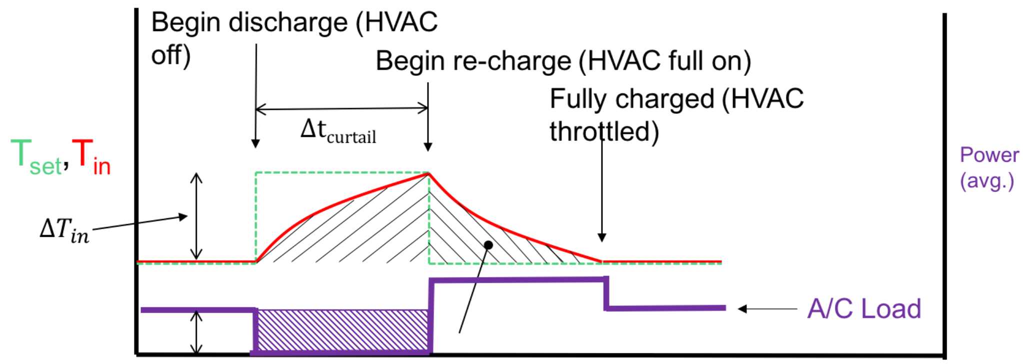

Figure G.3. Characterization of building SoC (summer).

Characterization in the summer cooling case (Tsp ≤ Tmax):

- Set point (ideal working temp) Tsp
- Occupants are allowed to turn off the HVAC system to tolerate the highest temperature, Tmax
- Discharge: Tsp → Tmax
- Charge: Tmax → Tsp
- SOC(t) = $\frac{T_{max} - T_{in}}{T_{max} - T_{sp}}$.

Characterization in the winter heating case (Tsp ≥ Tmin)

- Set point (ideal working temp) Tsp
- Occupants are allowed to turn off the HVAC system to tolerate the lowest temperature, Tmin
- Discharge: Tsp → Tmin
- Charge: Tmin → Tsp
- SOC(t) = $\frac{T_{in} - T_{min}}{T_{sp} - T_{min}}$.

G.5.11.1 Discharging Model

The purpose of the discharging model is to determine (1) the amount of energy supplied from an initial SoC, (2) the present SoC of the thermal storage, and (3) the maximum amount of useful energy that the storage is still able to supply.

Then, deriving the energy balance from Equation (G.1), we know the energy conservation should follow:

$$\Delta S_t = \Delta C_t - \Delta D_t - \Delta L_t \tag{G.7}$$

where

ΔS_t = the change of stored energy,
ΔC_t = the charged energy,
ΔD_t = the demand (service to grid), and

ΔL_t = the energy loss including all kinds of radiation, conduction, convection mentioned in Equation (G.1).

A smart grid algorithm may use this information to determine the actual SoC of the thermal storage. The SoC is calculated as follows:

$$SoC_t = \frac{S_t}{S_{\max}}, 0 \le SoC_t \le 1 \tag{G.8}$$

The stored energy at time interval t, S_t is determined by Equation (G.9). S_{t-1} is the stored energy at the previous time interval $t-1$. The maximum charged energy is determined by Equation (G.10), which is worked out from the first law of thermodynamics, relating the required thermal energy to the change of enthalpy of the lumped thermal mass inside the building.

$$S_t = S_{t-1} + \Delta S_t \tag{G.9}$$

$$S_{\max} = c_m \cdot M \cdot \left| T_{sp} - T_{\min}(T_{\max}) \right| \tag{G.10}$$

In which M, c_m denotes the overall thermal mass inside the building and corresponding specific heat; and T_{max} (T_{min}) the maximum (minimum) allowed temperature of the building, i.e., determined by the customers' setting. Another fixed variable by customers is the thermostat setting temperature T_{sp}. The amount of useful energy that can be supplied by the storage is determined by a minimum SoC value. The minimum SoC is determined from the intersection with the minimum (maximum) comfort temperature in winter (summer).

G.5.11.2 Charging Model

During charging from an empty state, the storage temperature is increased isothermally. Hence, electric power increases approximately linearly with the indoor temperature. It follows that when the charging process starts from an arbitrary SoC state, the indoor temperature of the air volume that needs a temperature increase determines the duration and the amount of electric energy.

The total required thermal energy to reach full charge is calculated as follows:

$$C_{tot,t} = (1 - SoC_t) \cdot S_{\max} \tag{G.11}$$

$$SoC_{\min} \le SoC_t \le 1 \tag{G.12}$$

where the longest duration of the charging process τ_t is calculated by

$$\tau_t = \frac{C_{tot,t}}{\Delta C_t}. \tag{G.13}$$

Remark G5.11.1:

We can simply substitute the full charge condition (SoC = 1) by any other value of partial charge condition (for example [SoC_t,1]) to compute the charging energy and duration for any other desired target SoC (computed from indoor temperature). It remains to compute ΔC_t, which is basically related to the COP and part load ratio and appears to be a linear interpolation with outdoor temperature. So the charging energy ΔC_t can be computed as follows:

$$\Delta C_t = a \cdot T_{amb,t} + b \tag{G.14}$$

The electric power consumption $P_{e,\mathrm{T}}$ of a future charging cycle with discrete future time T from a given SoC_t to fully charged conditions, is predicted as a linear function in time, as follows:

$$\begin{gathered} P_{e,\mathrm{T}} = P_{e,\mathrm{T}_i} + \frac{P_{e,\mathrm{T}_i+\tau} - P_{e,\mathrm{T}_i}}{\tau} \cdot \mathrm{T}, \\ 0 \le \mathrm{T} \le \tau \end{gathered} \tag{G.15}$$

where the period starts with electric power consumption P_{e,T_i} and ends with $P_{e,\mathrm{T}_i+\tau}$.

This electric energy change corresponds to ΔE_t, which needs to be calculated. Note that T is a time in the future when charging is initiated, which is a control variable for the smart control system.

The electric energy consumption of the future charging cycle is calculated with Equation (G.16), which is the integral of Equation (G.15)

$$E_{tot,\tau} = \frac{\tau}{2} \cdot \left(P_{e,\mathrm{T}_i} + P_{e,\mathrm{T}_i+\tau} \right) \tag{G.16}$$

G.5.12 Device Impact Metrics

None.

G.5.12.1 Energy Impact and Metrics

None.

G.5.12.2 Amenity Impacts Metrics

The only possible amenity metric for this model would be unmet load hours. Unmet load hours are any hours of operation when conditioned spaces are outside the throttling range for the heating or cooling controls. That is, they are the hours in a year that the HVAC system serving a space cannot maintain the space set point. In this initial design of the Battery-Equivalent Model, we ignore the unmet load hours because we are always trying to simulate the building model within the agreed-upon comfort band.

G.5.12.3 Equipment Impacts Metrics

The impact on the HVAC equipment's electrical or thermal stress and lifetime should be evaluated. The evaluation includes the following equipment impact metrics:

- lifecycle start/stop count
- depth of discharge (DOD)
- cycle duration
- maintenance cost.

G.6 Device Fleet

G.6.1 Default Fleet Characteristics (Instantiation)

Default fleet characteristics include the following:

- The size of the fleet represented: The actual number of HVAC units that are represented by the ones that were explicitly modeled. It is assumed that each air conditioner that is modeled is representative of a larger number of identical air conditioners. This sort of scaling greatly reduces the run time of the model, while still reasonably representing a large fleet of air conditioners. The default is 200.
- The initial indoor temperature: The initial indoor temperature for each individual building is set using a uniform distribution between 22.5°C and 23.5°C. Values were chosen based on a nationally representative temperature set point, which is 23°C.
- The energy efficiency of the building envelope: 50% of the buildings are of medium energy efficiency (corresponding to average resistance-capacitance (RC) values); 30% of the buildings are of low-efficient with small R & C values; the last 20% are high-efficient houses that have larger R & C values.
- Default temperature upper bounds (TMax) are chosen as 27°C for all the HVACs. This can be easily modified to follow any given distribution if needed.

G.6.2 Coordination Scheme

Once the availability of all air conditioners in the fleet has been determined, the total grid service request is divided equally among each available air conditioner and they each provide their service. Note that during the time step, if a given air conditioner is providing a service and it reaches a SoC upper/lower boundary, it will cease to perform the service and will maintain operation at the limiting SoC.

G.6.3 Example Usage

We provide a simple example of using this HVAC fleet model to provide ancillary services. As shown in Figure G.4, a good match has been achieved between the grid-required amount and the actual response from the fleet consisting of 200 ON/OFF units. The simulation lasts one day (96 time steps) with 15 minutes for each time step. The grid service signal (marked by red) was randomly generated with reasonable magnitude, while the black curve represents the overall response from this fleet.

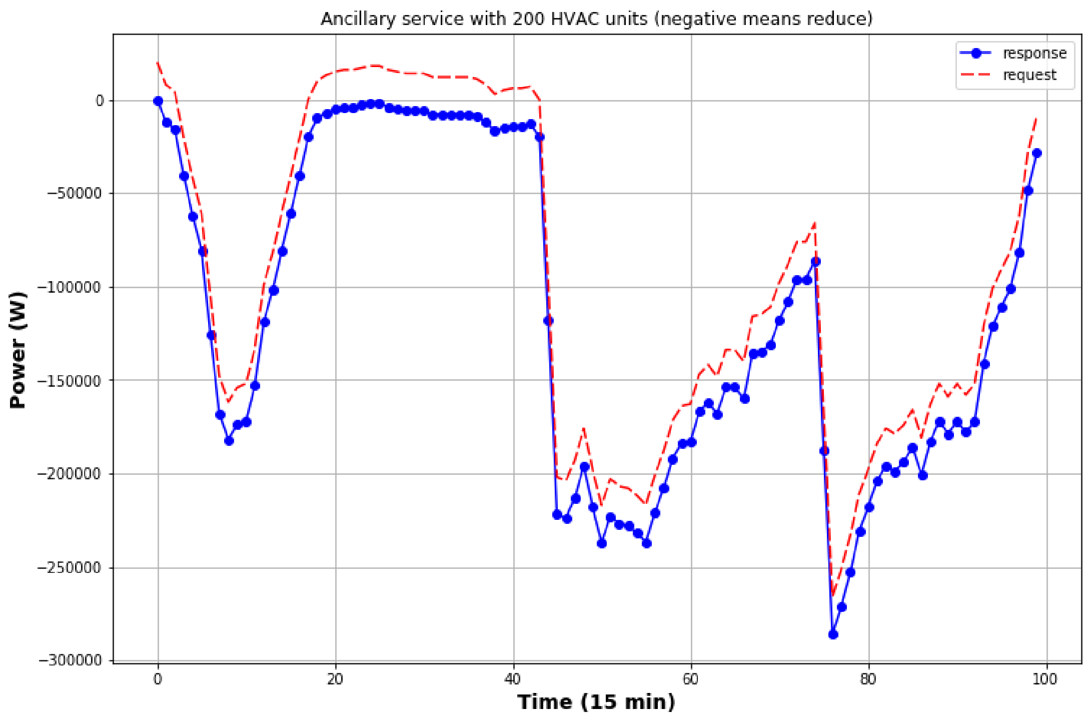

Figure G.4. Typical grid services with the HVAC fleet.

Appendix H – Commercial Refrigeration Systems

H.1 Basic Device Purpose

Refrigeration systems in supermarkets and convenience stores operate continuously to maintain proper product storage conditions, and these refrigeration systems can account for 40% or more of the electrical energy consumption of a supermarket or convenience store. The potential to store energy within refrigerated food products presents convenience store and supermarket operators with an opportunity to participate in utility-sponsored demand-response programs, whereby electricity usage can be shifted or reduced during peak periods. Given that there could be several hundred or even thousands of convenience stores within the service area of a power generating station, this would represent a significant load reduction during peak generation.

H.2 Standard Controls and Normal Operational Modes

The standard control for the commercial refrigerant units is to use different thermostats and on/off operations for performing set point-based control of the refrigeration unit. The thermostat comprises a temperature sensor, control logic, and relay circuity. For a given user set point temperature and acceptable deadband the thermostats turn on cooling as the shelf temperature deviates from the set point.

Typical operational states are as follows:

- Low Temperature (LT) Off, Medium Temperature (MT) Off
  - LT On, MT Off
  - LT Off, MT On
  - LT On, MT On
- If variable/multi-speed compressor
  - % capacity (variable speed)
  - operational stage (multi-stage)
  - delay appliance load (DL)
  - temporary load reduction (TLR)
  - increase load (IL)
- control parameters:
  - refrigeration case temperature (°C)
  - refrigeration case set point (°C)
  - short-cycling prevention

Other measurements:

- ambient temperature
- defrost.

Due to the complexity, we do not model the flexibility when the system is in a defrost cycle.

H.3 Equipment Availability and Usage Patterns

The electrical energy consumption of the refrigeration systems in supermarkets, grocery stores and convenient stores is responsible for approximately 11% of the total electrical energy consumption in the U.S. commercial building sector. Worldwide, commercial refrigeration accounts for 90 million pieces of equipment, including condensing units, stand-alone equipment, and centralized systems

Commercial refrigeration systems are used to store products such as frozen foods, beverages, deli and dairy products, and produce at temperatures that maintain food safety and quality. The products are typically stored within two temperature ranges: the LT range of – 40°C to -18°C and the MT range of -18°C to 5°C. Stand-alone or self-contained commercial refrigeration cabinets include small vertical open, vertical reach-in, and tub-type cabinets, as well as service deli cabinets, ice-cream cabinets, ice makers, and food and beverage vending machines. These systems have an integrated direct expansion refrigeration system, which includes an evaporator located in an insulated compartment, as well as a compressor and condenser. Because the refrigeration system in a stand-alone cabinet is sealed at the factory, no additional refrigerant piping is required. Because the cabinet is an indoor application, the energy consumption of a self-contained cabinet remains uniform throughout the year. However, the energy absorbed from the stored product is rejected to the occupied retail space, adding to the heating, ventilation, and air-conditioning (HVAC) load. Centralized commercial refrigeration systems typically consist of one or more compressor racks located in either an indoor or outdoor machine room, and piping to distribute the refrigerant or a secondary fluid to the refrigerated display cases located throughout the sales space in the store and the walk-in coolers and freezers located in the back room of the facility. Refrigerant piping also connects the compressor rack(s) to the remote condensers located outside. The control of refrigerated container temperature and humidity constitutes the main power consumption of these systems.

Due to the complexity of modeling human-involved activity as well as experience limitations, we do not consider effects such as restocking (and overstocking). As a first step in such a study, we assume a rather static load status. However, human-involved models for additional usage patterns or customer activities can be easily added to make the existing model more complicated.

H.4 Change in Power Output Resulting from Response

A commercial refrigeration system can typically be controlled as on/off, DL (delay appliance load), TLR (temporary load reduction), and IL (increase load). The main control parameters are the refrigeration case temperature (°C) and the refrigeration case set point (°C) with a constraint of short-cycling prevention. In the case of refrigeration systems that can respond to grid events, the compressors can be switched on or off within the constraint of compressor short cycling and current environmental conditions, e.g., in the display cases.

Compressors represent the main controllable equipment in the commercial refrigeration systems. The compressor equipment are of the following type:

- compressor racks with/without a variable-speed compressor
- a condensing unit that generally has single-speed compressor

- stand-alone units (single-speed compressor).

For single-speed compressor units when cooling, the device power consumption will change as the mode changes; e.g.:

- Mode change from Run to Idle or Run to Off
  - Reduction in real power consumption.
  - Corresponding reduction in reactive power consumption.
  - Associated time lags.
- Mode change from Off to Run or Idle to Run
  - Increase in real power consumption.
  - Corresponding increase in reactive power consumption.
  - Associated time lags.
- Mode change from Run to DL
  - Reduce power draw by >15% during delay period.
  - Defrost is delayed until after the event unless "safe maximum" temperature is reached and defrost is required for compressor operation.
    - If in defrost mode when signal is received, continue in that mode until the cycle is complete.
  - May delay icemaker cycles.
- Mode change from Run to TLR
  - Reduce power draw by >50% during delay period.
  - The compressor is turned off until compartment(s) temperature reaches the "safe maximum". After that, the compressor operates at minimum cycle time to maintain compartment(s) temperature within the "safe maximum"+ deadband width.
  - Defrost is disabled unless the "safe maximum" temperature is reached and defrost is required for compressor operation.
    - If in defrost mode when signal is received, continue in that mode until the cycle is complete.
  - May delay icemaker cycles.
- Mode change from Run to IL
  - Increase load by >15% during delay period.
  - May initiate icemaker or defrost cycles.
    - Operate the compressor until the minimum compartment(s) temperatures are reached.
- Mode change from DL, TLR, IL to Run
  - Resume normal operation with the compartment(s) temperature set point identical to what it was before the grid services event.
  - Randomize end-times within the fleet of devices to prevent load surging.

H.5 Device Model

H.5.1 Assumptions

In addition to the parameter assumptions listed above, the following additional assumptions are applied to the battery-equivalent refrigeration system model:

- The model must be able to be commanded to Off, DL, TLR, and IL operating *modes*.
- Various temperatures should be recorded inside the refrigeration system.
- The model must provide a means of measuring or estimating the refrigerator's virtual battery-equivalent state of charge (SoC).
- The saturation temperature of condenser is set to be

$$T_{sat,condenser} \approx T_{ambient} + 10^{\circ} F$$

.

- The enthalpy will not change after passing the expansion valve.
- The refrigeration system is a cold storage device consisting of a .LT.) cooling capacity and a .MT.) cooling capacity.
- The LT cooling capacity is approximately 18 kW at a saturated evaporating temperature of −29°C.
- The MT cooling capacity is approximately 35 to 53 kW at a saturated evaporating temperature of −4°C.
- Heat transfer into the conditioned thermal space is 100% efficient. That is, it is assumed there are no heat losses in the thermal piping from the storage to the conditioned space.
- The refrigeration system, as a virtual battery, will never become over- or under-charged. That is, the temperature inside will stay below the freezing/melting point of the refrigerated product.
- To operate the device in a safe/acceptable manner, the system controller will need to know the following:
  - thermal energy capacity
  - fixed charge and discharge power levels
  - end-user limits (temperature excursion, etc.)
  - time limits (clock, duration, etc.)
  - equipment limits (minimum compressor cycle time, short cycling, depth of cycles, etc.)
  - defrost schedule.

H.5.2 Parameters/Equipment Characteristics

Many of the assumed parameters for an individual refrigeration system are determined at the start of the creation of the fleet. Whenever possible, reasonable statistical distributions are assumed to provide variety for the refrigeration system fleet. The assumed parameters and distributions are as follows:

- change in the refrigeration system SoC during *characterization testing*
- temperature of the low-temperature display case, T_{LT}

- temperature of the medium-temperature display case, T_{MT}
- time in idle operating *mode*, t_{idle}
- steady-state electrical real electrical power during charge operating *mode*, P_{charge}
- steady-state electrical voltage-current phase angle during charge operating *mode*, θ_{charge}
- time in charge operating *mode*, t_{charge}
- steady-state real power consumption of the compressor (and other equipment) during discharge operation, P_{comp}
- steady-state voltage-current phase angle of the pump (and other equipment) during discharge operation, θ_{comp}
- time in discharge operating *mode*, $t_{discharge}$
- ambient air temperature, T_{amb}
- saturated evaporator low temperature $T_{sat,LT\ evap}$
- LT compressor efficiency η_{LT}
- MT compressor efficiency η_{MT}
- duration of short-cycle charge operation in seconds, $t_{short-cycle}$
- thermal energy delivered to the thermal reservoir during a short-cycle operation, $q_{short-cycle}$
- minimum compressor cycle time, t_{min}
- thermostat set point, $T_{setpoint}$
- thermostat deadband, $T_{deadband}$.

H.5.3 Boundary Conditions

The boundary conditions considered in this model are as follows:

- upper and lower bounds for both temperatures and humidity in display cases
- ambient temperature.

As mentioned before, product removal and stocking behaviors are skipped in this model.

H.5.4 Variables

Variables are values to be calculated by the model. They are not model parameters but will appear in the Physical Equation section as inputs in the functions defining those parameters and thus must be defined before being used. This section provides a place for defining the variables, as follows

- time to discharge the refrigeration system from 100% to 0%, $t_{100\%\text{-}discharge}$
- thermal energy capacity of the refrigeration system, $q_{capacity}$
- thermal energy lost to environment from the refrigeration system, q_{losses}

- thermal power flow to environment from the refrigeration system, $\dot{q}_{losses}$
- thermal energy transferred to the refrigeration system during charge *mode* operation, q_{charge}
- thermal energy transferred to the refrigeration system during charge *mode* operation after accounting for thermal reservoir losses, $q_{charge\ net}$
- thermal power transferred to the thermal reservoir during charge *mode* operation, $\dot{q}_{charge}$
- thermal storage SOC
- steady-state real power consumption of the refrigeration system (compressor and fan) during discharge operation, $P_{discharge}$
- thermal power flow out of the thermal reservoir, $\dot{q}_{discharge}$
- thermal power flow into the building envelope, $\dot{q}_{indoor}$
- partial load ratio (*PLR*) defined as the ratio of actual cooling provided in a given time period to the maximum possible cooling that could have been provided in a time period.

H.5.5 Physical Equations

A reference refrigeration system, as shown in Figure H.1, which comprises the typical components found in most U.S. supermarket refrigeration systems, was used to determine the impact of system operating strategies on product temperature. An example refrigeration system, which uses R-404A refrigerant, has a LT cooling capacity of approximately 18 kW at a saturated evaporating temperature of −29°C and a MT cooling capacity of approximately 35 to 53 kW at a saturated evaporating temperature of −4°C. Three open vertical display cases, each 3.7 m in length, constitute the LT load. The MT load consists of two open vertical display cases, each 3.7 m in length, as well as a “false” load provided by a plate heat exchanger and glycol loop.

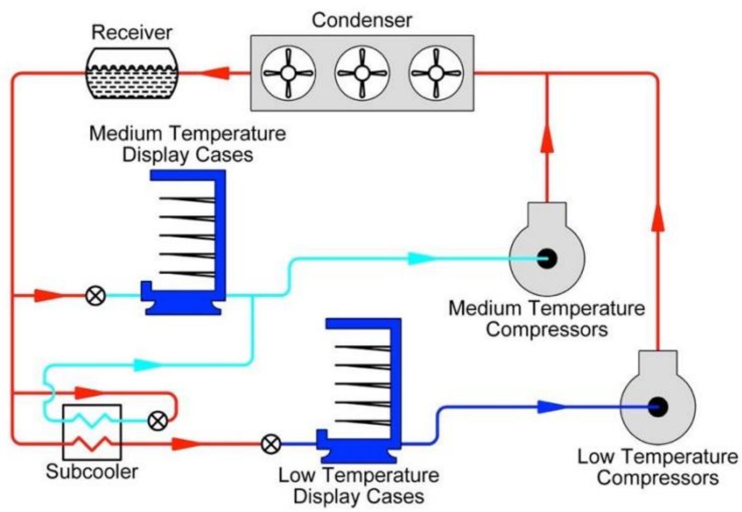

Figure H.1. A laboratory-scale supermarket refrigeration system.

In the following sections, we will first go through a physics-based model description, which is easy to follow but difficult to calculate due to the unknown system parameters. Later, we will follow the classical resistance-capacitance (RC) model, also called the lumped capacitance or network model, which is constituted with electrical analogue pattern with resistance (R) and capacitance (C). Such an RC model has been widely used in the air-conditioner models.

This specific system contains two LT and two MT reciprocating compressors as well as an air-cooled condenser. The compressor rack and air-cooled condenser are installed in a temperature- and humidity-controlled "outdoor" environmental chamber, while the refrigerated display cases are installed in a separate temperature- and humidity-controlled "indoor" environmental chamber. For both chambers, the temperature can be controlled between −18 to 54°C and the humidity can be controlled between 30 to 90%. Thus, the air-cooled condenser can be exposed to typical outdoor ambient conditions, while the refrigerated display cases operate in an environment typical of that found in the sales area of a supermarket.

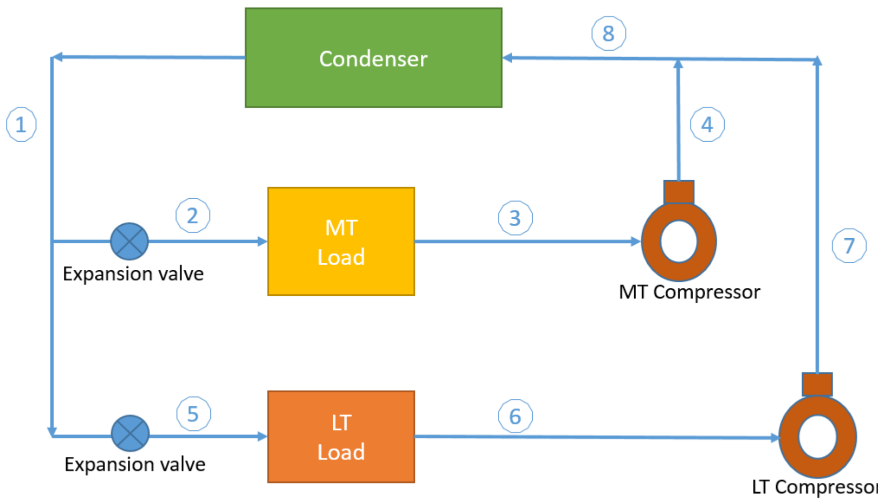

Figure H.2. Components of a supermarket refrigeration system.

H.5.5.1 Condenser

The condenser of a refrigerator is used to get rid of heat extracted from the interior of the unit to the outside air. To compute the exact heat exchange, we need enthalpy values at point 8 and 1 in Figure H.1. So we denote the value as follows:

$$\dot{Q}_{Condenser} = \dot{m}_{Total}(h_8 - h_1) \tag{H.1}$$

where h_8 and h_1 are determined by temperature and pressure at that moment.

Usually, the saturation temperature of condenser is set to be

$$T_{sat,condenser} \approx T_{ambient} + 10^{\circ} F \ . \tag{H.2}$$

By searching the thermodynamics table, we first find the corresponding temperature w.r.t. saturation temperature.

Once the temperature and pressure are fixed, the enthalpy will be fixed under this condition. Therefore, h_1 is considered as known by looking for corresponding table.

H.5.5.2 Coefficient of Performance

We use the coefficient of performance (COP) to characterize the overall efficiency of the system. Typical COP values for MT (LT) display cases range from 2.69 (1.55) to 4.86 (2.58), which depends on the ambient temperature.

$$COP = \frac{\dot{Q}_{MT} + \dot{Q}_{LT}}{\dot{W}_{Actual,MT} + \dot{W}_{Actual,LT}} \tag{H.3}$$

H.5.5.3 Discharging/Charging Services for MT

Let us consider the MT case (the same discussion applies for the LT case).

Assume the allowed temperature range for MT display case is $[T_{3\min}, T_{3\max}]$.

Therefore, the SoC can be defined as

$$SoC_{MT}(T_3) = \frac{\dot{Q}_{MT}}{\dot{Q}_{MT\max}} \tag{H.4}$$

where T3 represents the current display temperature.

H.5.5.4 Discharging Model

The purpose of the discharging model is to determine

- • the amount of energy supplied from an initial SoC
- • the present SoC of the refrigerator
- • the maximum amount of useful energy that the storage is still able to supply.

As discussed above, T_{3max} (T_{3min}) is the maximum (minimum) allowed temperature of the MT display case, as determined by the customer's setting and food/drink requirement. Another fixed variable determined by the customer is the thermostat setting temperature T_3.

The amount of useful energy that can be supplied by the refrigerator (thermal storage) is determined by a minimum SoC value.

Finally, it is obvious to calculate the potential discharging energy under the current temperature setting following the derivation for $\dot{W}_{Actual,MT}$ by plugging in relevant temperature values.

H.5.5.5 Charging Model

During charging from the current state (T_3) to the full state (T_{3min}), electric power increases approximately the same as determined by calculating $\dot{W}_{Actual,MT}$ through the whole process described in the previous section.

Based on the preceding physics-based analysis, we built an RC model similar to that used in the air-conditioner system. Instead of simulating the indoor temperature, we are modeling the case temperature and food temperature in the following model.

Thermal Capacitance

The thermal capacitance of different devices can be estimated by

$$C_k = \mu c_A \rho_A V_k, \tag{H.5}$$

where

C_k = the thermal capacitance of device type k,
μ = the correction factor to account for additional thermal mass besides air ($\mu = 1.2$),
c_A and ρ_A = the specific heat and the density of the air, respectively, and
V_k = the typical internal volume of device type k.

Thermal Resistance

The thermal resistance of different devices can be estimated by

$$R_k = \frac{r_k}{S_k}, \tag{H.6}$$

where R_k is the thermal resistance of device type *k*, r_k is the R-value of the insulation of device type *k*, and S_k is the surface area of device type *k*.

Rated Power

The compressor and condenser account for majority of power consumed by commercial refrigeration equipment. Commercial refrigeration equipment can be classified into two categories: split-system and self-contained systems. Split-system configurations have condenser units and a compressor unit that are located remotely. Self-contained units have all of the components, including the condenser, contained in a single package. For self-contained refrigeration systems, the rated power is readily available. For split-system refrigeration systems, however, the procedure for obtaining the rated power is not straightforward because condenser units and a compressor unit may serve multiple devices. The following formula is proposed to estimate the rated powers for the split-system refrigeration systems:

$$P_k = \frac{CC_k}{\sum_q^{mc} CC_q}(P_{com} + P_{con}), \tag{H.7}$$

where

P_k = the rated power,
CC_k = the cooling capacity,

mc	=	the number of devices that are served by the same compressor and the same condenser, and
P_{com} and P_{con}	=	the rated power of compressor and the condenser, respectively.

Refrigerator RC Temperature Model

The refrigeration RC temperature model includes two coupled ordinary differential equations (ODEs)

- X1: case temperature
- X2: food temperature.

The RC model for refrigeration system can be described as follows:

$$\frac{dx_1}{dt} = \left[\frac{T_{amb} - x_1}{R_{case}} + \frac{x_2 - x_1}{R_{food}} - C_1 \times Q_{sens} + Q_{heat} + \frac{(T_{amb} - x_1) \times \dot{m}_{Cair} \times Infil}{C_{air}} \right]$$

$$\frac{dx_2}{dt} = \frac{x1 - x2}{R_{food} \times C_{food}} \tag{H.8}$$

Trained parameters for the model are listed in Table H.1.

Table H.1. Trained parameters for the Refrigeration RC Temperature model.

Variable Names	Values	Units
A5		
Case Volume	131.13	ft^3
Product Volume fraction	0.6	
Air Volume	52.452	ft^3
Air Mass	3.9339	lb
Air C	0.944136	Btu/R
Air C	**1793.031**	**J/K**
Product Volume	78.678	ft^3
Product fraction water	0.5	
Product Air Mass	2.950425	lb
Product Water Mass	2439.018	lb
Product Air C	0.708102	Btu/R
Product Water C	2439.018	Btu/R
Product C	2439.726	Btu/R
Product C	**4633342**	**J/K**
Discharge Air Velocity	200	fpm
Discharge grille length	12	ft
Discharge grille width	0.333333	ft
Discharge Volume flow	800	cfm
Max Infil Coeff	864	Btu/h-F

Variable Names	Values	Units
Max Infil Coeff	455.7897	W/K
Case length	12	ft
Case Height	6.833333	ft
Case Depth	3	ft
Case Surface	195	ft^2
R-Value	10	h-ft^2-F/Btu
Rcase	0.051282	h-F/Btu
Rcase	**0.097211**	**K/W**
Product Surface Area	460	ft^2
h	3.5	Btu/h-ft^2-R
Rfood	0.000621	h-F/Btu
Rfood	**0.001177**	**K/W**

H.5.6 End-Use Load

The end-use load considered here is to provide sufficient cooling for both MT and LT applications in the commercial refrigeration system.

H.5.7 Parasitic Loads

This includes the housekeeping power and heat leakage loss to ambient.

H.5.8 Possible Device Responses

If any grid services are requested, the commercial refrigeration fleet will determine if it has the capability to provide grid services. The control logic for providing grid services depends on the type of service requested. If there is a request to add load, an additional number of commercial refrigeration systems will turn on as long as the commercial refrigeration system is below the maximum allowable temperature and has the minimum required load-add capacity. If there is a request to shed load, a certain number of commercial refrigeration system will be turned off (if it would otherwise have been operating) as long as the temperatures are in the predefined range for MT and LT display cases.

H.5.9 Constraints on Device Response

Avoid short cycling for compressors.

Ensure that all refrigerated content is kept within predefined temperature ranges to meet food safety requirements.

H.5.10 Device Model Validation

The Oak Ridge National Laboratory’s laboratory setup for commercial refrigeration consists of two LT compressors and two MT compressors using R-404A refrigerant. Each pair of compressors consists of one variable-speed compressor (capable of modulating capacity from 10% to 100%) and one fixed speed compressor. Specifications for the compressors are listed in Table H.2. The MT load consists of two open vertical display cases (example photo in Figure H.3), each 12 ft (3.7 m) in length, and a “false” load provided by a plate heat exchanger and glycol loop.

Table H.2. Compressor specifications for laboratory setup.

Compressor Type	Temperature Level	Capacity Control	Refrigerating Capacity, kBtu/h (kW)[a]	Power, kW[a]
Reciprocating	LT	Variable	32.0 (9.4)	5.70
Reciprocating	LT	Fixed	32.0 (9.4)	5.70
Reciprocating	MT	Variable	92.3 (27.1)	8.50
Reciprocating	MT	Fixed	92.3 (27.1)	8.50
Scroll	LT	Variable	32.3 (9.5)	5.20
Scroll	LT	Fixed	32.3 (9.5)	5.20
Scroll	MT	Variable	56.3 (16.5)	5.23
Scroll	MT	Fixed	56.3 (16.5)	5.23

(a) Refrigerating capacity and power are given for the following operating conditions using R-404A: LT: -20°F (-29°C) evaporating temperature, 105°F (41°C) condensing temperature; MT: 25°F (-3.9°C) evaporating temperature, 105°F (41°C) condensing temperature.

Figure H.3. Medium temperature display case in test chamber.

H.5.11 Translating Device Model to Battery-Equivalent Model Parameters

Now we start translating the above thermal model into a battery equivalent model.

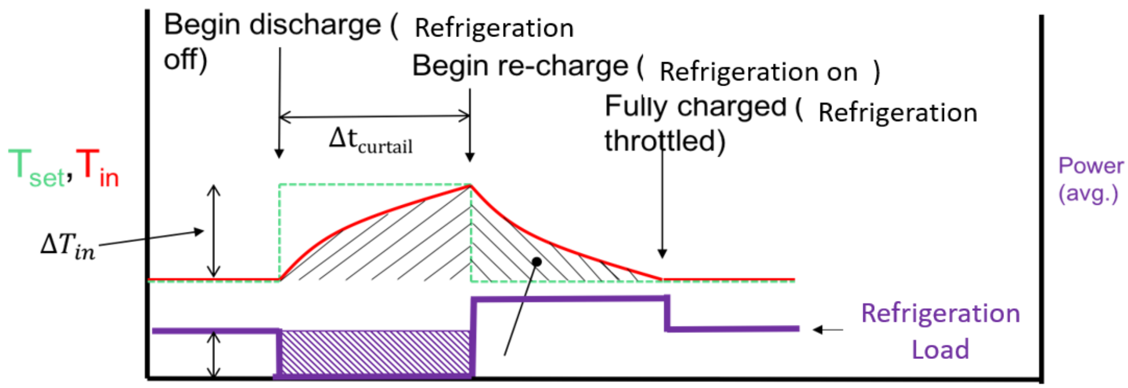

Figure H.4. Characterization of display case SoC.

Characterization:

- Set point (ideal working temp) Tsp
- Occupants allow turn off display case to tolerate highest temperature Tmax
- Discharge: Tsp → Tmax
- Charge: Tmax → Tsp
- SOC(t) = $\frac{T_{max} - T_{in}}{T_{max} - T_{sp}}$.

Similar to the Battery-Equivalent Model defined for the air-conditioner systems, we introduce charging/discharging behaviors for the commercial refrigeration system.

H.5.11.1 Discharging Model

The purpose of the discharging model is to determine (1) the amount of energy supplied from an initial SoC, (2) the present SoC of the thermal storage, and (3) the maximum amount of useful energy that the storage is still able to supply.

Then deriving the energy balance from Equation (G.1), we know the energy conservation should follow:

$$\Delta S_t = \Delta C_t - \Delta D_t - \Delta L_t \tag{H.9}$$

where

ΔS_t = denotes the change of stored energy,
ΔC_t = the charged energy,
ΔD_t = the demand (service to grid), and
ΔL_t = the energy loss, including all kinds of radiation, conduction, convection mentioned in Equation (G.1).

A smart grid algorithm may use this information to determine the actual SoC of the thermal storage. The SoC is calculated by:

$$SoC_t = \frac{S_t}{S_{\max}}, 0 \le SoC_t \le 1 \tag{H.10}$$

The stored energy at time interval t, S_t is determined by Equation (H.11). S_{t-1} is the stored energy at the previous time interval $t-1$. The maximum charged energy is determined by Equation (H.12), which is worked out from the first law of thermodynamics, relating the required thermal energy to the change of enthalpy of the lumped thermal mass inside the building.

$$S_t = S_{t-1} + \Delta S_t \tag{H.11}$$

$$S_{\max} = c_m \cdot M \cdot \left| T_{sp} - T_{\min}(T_{\max}) \right| \tag{H.12}$$

in which M, c_m denote the overall thermal mass inside the display case and corresponding specific heat, and T_{max} (T_{min}) the maximum (minimum) allowed temperature of the display case, as determined by the customer's setting. Another fixed variable set by the customer is the thermostat setting temperature T_{sp}. The amount of useful energy that can be supplied by the storage is determined by a minimum SoC value.

H.5.11.2 Charging Model

During charging from an empty state, the storage temperature is increased isothermally. Hence, electric power increases approximately linearly with the case temperature. It follows that when the charging process starts from an arbitrary SoC, the case temperature of the air volume that needs a temperature increase determines the duration and the amount of electric energy.

The total required thermal energy to reach full charge is calculated as follows:

$$C_{tot,t} = (1 - SoC_t) \cdot S_{\max} \tag{H.13}$$

$$SoC_{\min} \le SoC_t \le 1 \tag{H.14}$$

where, the longest duration of the charging process τ_t is calculated by

$$\tau_t = \frac{C_{tot,t}}{\Delta C_t} . \tag{H.15}$$

Remark:

We can simply substitute the full charge condition (SoC = 1) by any other value partial charge condition (for example [SoC_t,1]) to compute the charging energy and duration for any other desired target SoC (computed from the case temperature). It remains to compute ΔC_t, which is basically related to the COP and PLR and appears to be a linear interpolation with ambient temperature. So the charging energy ΔC_t can be computed as follows:

$$\Delta C_t = a \cdot T_{amb,t} + b \tag{H.16}$$

The electric power consumption $P_{e,\mathrm{T}}$ of a future charging cycle with discrete time T in the future, from a given *SoC*$_t$ to fully charged conditions, is predicted as a linear function in time as follows:

$$P_{e,\mathrm{T}} = P_{e,\mathrm{T}_i} + \frac{P_{e,\mathrm{T}_i+\tau} - P_{e,\mathrm{T}_i}}{\tau} \cdot \mathrm{T}, \quad 0 \le \mathrm{T} \le \tau \tag{H.17}$$

where the period starts with electric power consumption P_{e,T_i} and ends with $P_{e,\mathrm{T}_i+\tau}$.

This electric energy change corresponds to ΔE_t, which needs to be calculated. Note that T is a time in the future when charging is initiated, which is a control variable for the smart control system.

The electric energy consumption of the future charging cycle is calculated using Equation (H.18), which is the integral of Equation (H.17)

$$E_{tot,\tau} = \frac{\tau}{2} \cdot \left(P_{e,\mathrm{T}_i} + P_{e,\mathrm{T}_i+\tau} \right) \tag{H.18}$$

H.5.12 Device Impact Metrics

H.5.12.1 Energy Impact and Metrics

The energy impact metrics include

- energy consumption
- energy cost
- energy efficiency.

The thermal losses are slightly reduced, but the case temperature will still need to come back to the set point temperature after the shed event has completed.

H.5.12.2 Amenity Impacts Metrics

Not applicable

H.5.12.3 Equipment Impacts Metrics

The impact on the refrigeration equipment's electrical or thermal stress and lifetime should be evaluated. The evaluation includes the following equipment impact metrics:

- lifecycle count
- cycle duration
- maintenance cost.

H.6 Device Fleet

H.6.1 Default Fleet Characteristics (Instantiation)

Default fleet characteristics include the number of refrigeration systems to model that are explicitly modeled. The default is 50.

H.6.2 Coordination Scheme

Once the availability of all the commercial refrigeration systems in the fleet has been determined, the total grid service request is divided equally among each available commercial refrigeration system and they each provide their service. Note that during the time step, if a given commercial refrigeration system is providing a service and it reaches a limitation (either high or low SoC) it will cease to perform the service and will maintain operation at the limiting SoC.

H.6.3 Example Usage

As shown in Figure H.5, at 18:30 the average temperature of the 48 product simulators within the display case was −3.56°C, and the display case discharge air temperature was approximately −3.89°C. The supply of refrigerant to the display case was turned off at 18:30, and the air temperature and product temperature began to rise. As shown in Figure H.5, by 21:00 (2.5 hours after turning off the refrigeration), the average product temperature had risen by approximately 5.5°C to 2.33°C and the discharge air temperature had risen to 6.11°C. At 21:00, the refrigerant supply to the display case was turned on, and by 0:40, the product temperature had returned to −3.56°C, and the discharge air temperature was −4.56°C.

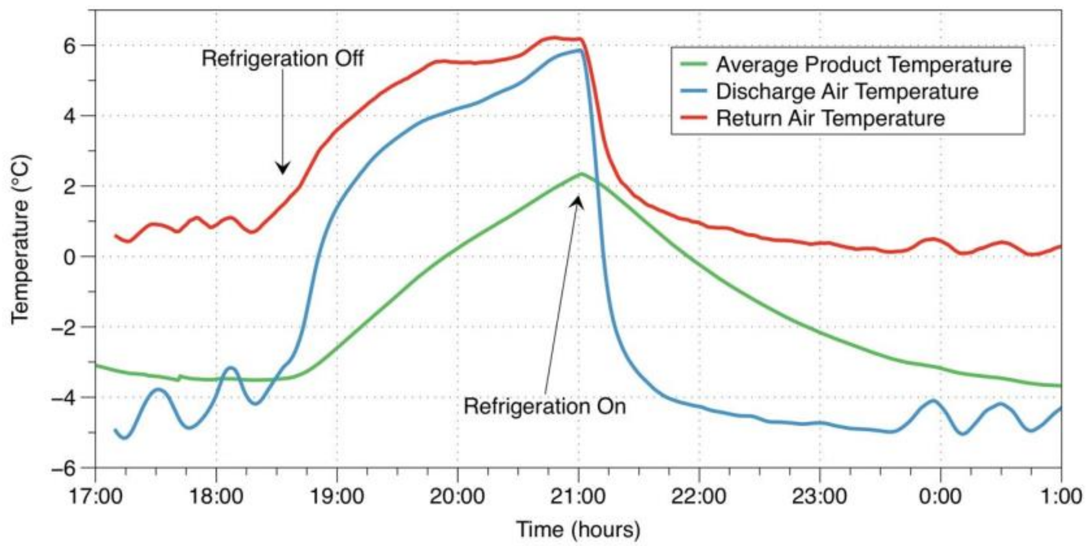

Figure H.5. Product and air temperatures in a medium temperature refrigerated display case.

Thus, the thermal mass of the products in the display case was such that during a 2.5-hour period with no refrigeration, the product temperature increased by 5.5°C, or roughly 2°C per hour. In addition, it took approximately 3.5 hours for the product to return to its initial temperature after the refrigeration was turned on. Note that this represents a worst-case scenario, because the display case used in this study was an open, multi-deck display case, in which a large percentage of the heat load on the case is due to infiltration of warm moist air into the case. If a doored display case was used, infiltration would be greatly reduced and the “cold” would remain within the case for a longer period. Thus, the product temperature would rise less over time. Regardless of display case type, an additional strategy that could be used during demand-response events would be to turn off display case lighting and reduce anti-sweat heater power and evaporator fan speed to reduce the heat load on the display case.

Finally, we provide a simple example of using this commercial refrigeration fleet model to provide ancillary services. As shown in Figure H.6, a good match has been achieved between the grid-required amount and the actual response from the fleet consisting of 50 units. The simulation lasts one day (96 time steps) with 15 minutes for each time step. Note that the grid service signal (marked by red) was randomly generated with reasonable magnitude, while the blue curve represents the overall response from this fleet.

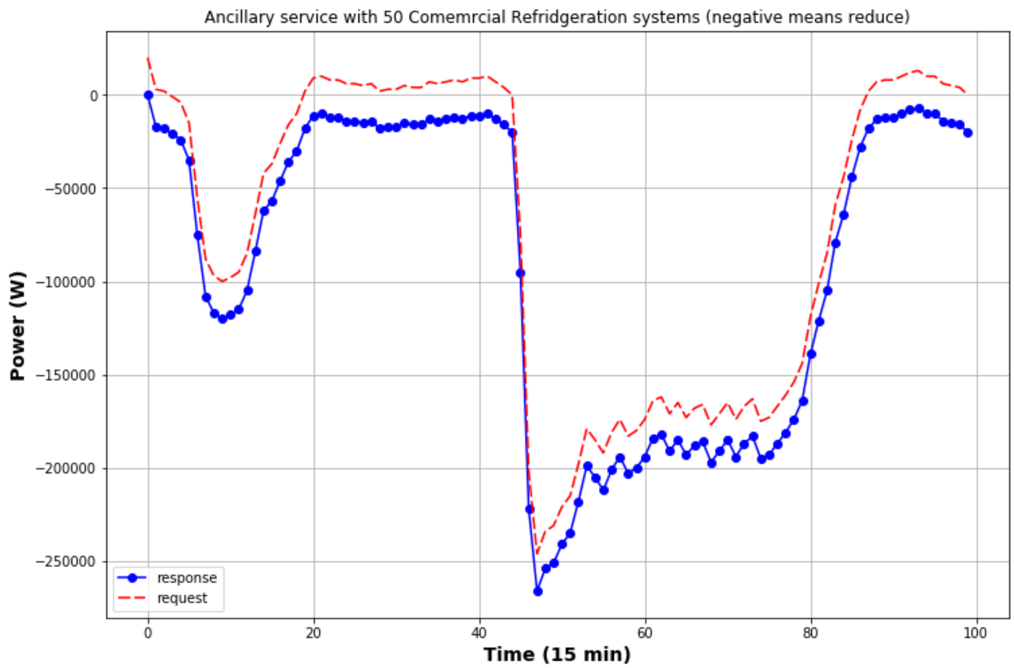

Figure H.6. Typical grid services with a commercial refrigeration fleet.

Appendix I – Author Index

Listed below is a summary of the primary points of contact and contributors for each of the eight devices and grid services:

Table I.1. General project contributors.

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Table I.2. Device specific contributors. Key **points of contact** shown in **bold**.

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Table I.3. Grid service specific contributors. Key **points of contact** shown in **bold.**

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