



A System-of-Systems Approach for Integrated Energy Systems Modeling and Simulation

Preprint

Saurabh Mittal, Mark Ruth, Annabelle Pratt,
Monte Lunacek, Dheepak Krishnamurthy, and
Wesley Jones

National Renewable Energy Laboratory

*Presented at the Society for Modeling & Simulation International
Summer Simulation Multi-Conference*

Chicago, Illinois

July 26–29, 2015

**NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy
Laboratory (NREL) at www.nrel.gov/publications.

Conference Paper
NREL/CP-2C00-64045
August 2015

Contract No. DE-AC36-08GO28308

NOTICE

The submitted manuscript has been offered by an employee of the Alliance for Sustainable Energy, LLC (Alliance), a contractor of the US Government under Contract No. DE-AC36-08GO28308. Accordingly, the US Government and Alliance retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Available electronically at SciTech Connect <http://www.osti.gov/scitech>

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
OSTI <http://www.osti.gov>
Phone: 865.576.8401
Fax: 865.576.5728
Email: reports@osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312
NTIS <http://www.ntis.gov>
Phone: 800.553.6847 or 703.605.6000
Fax: 703.605.6900
Email: orders@ntis.gov

Cover Photos by Dennis Schroeder: (left to right) NREL 26173, NREL 18302, NREL 19758, NREL 29642, NREL 19795.

NREL prints on paper that contains recycled content.

A System-of-Systems Approach for Integrated Energy Systems Modeling and Simulation

Saurabh Mittal, Mark Ruth, Annabelle Pratt, Monte Lunacek,
Dheepak Krishnamurthy, Wesley Jones
National Renewable Energy Laboratory (NREL), Golden, CO USA
{saurabh.mittal, mark.ruth, annabelle.pratt, monte.lunacek,
dheepak.krishnamurthy, wesley.jones}@nrel.gov

ABSTRACT

Energy systems integration combines energy carriers, including electricity, with infrastructures, to maximize efficiency and minimize waste. In order to study systems at a variety of physical scales—from individual buildings to distribution systems—interconnected through these energy infrastructures, NREL is developing an Integrated Energy System Model (IESM), with an initial focus on the electricity system. Today’s electricity grid is the most complex system ever built—and the future grid is likely to be even more complex because it will incorporate distributed energy resources (DERs) such as wind, solar, and various other sources of generation and energy storage. The complexity is further augmented by the possible evolution to new retail market structures that would provide incentives to owners of DERs to support the grid. The IESM can be used to understand and test the impact of new retail market structures and technologies such as DERs, demand-response equipment, and energy management systems on the system’s ability to provide reliable electricity to all customers. The IESM is composed of a power flow simulator (GridLAB-D), building and appliance models including home energy management system implemented using either GAMS or Pyomo, a market layer, and is able to include hardware-in-the-loop simulation (testing appliances such as air conditioners, dishwashers, etc.). The IESM is a system-of-systems (SoS) simulator wherein the constituent systems are brought together in a virtual testbed. We will describe an SoS approach for developing a distributed simulation environment. We will elaborate on the methodology and the control mechanisms used in the co-simulation illustrated by a case study.

Author Keywords

Co-simulation, GridLAB-D, optimization, DEVS, system-of-systems, integrated energy systems, Discrete-event simulation, Smart Grid

ACM Classification Keywords

I.6 SIMULATION AND MODELING: I.6.1 Simulation Theory, I.6.5 Modeling development, I.6.3 Applications, I.6.8 Types of simulation

1. INTRODUCTION

Energy systems integration (ESI) is an evolving paradigm wherein energy carriers such as electricity, thermal pathways, and fuels will be brought together with infrastructures such as communications, water, and transportation to maximize efficiency and minimize energy waste [1]. An energy system transformation already under way is that of the electricity grid, which is being infused with communications technologies to form a “Smart Grid,” and tied to the transportation infrastructure through the introduction of electric vehicles at scale. A key driver for the electricity grid’s evolution is the proliferation of DERs, including distributed renewable generation (such as photovoltaics [PV]) and distributed storage. Additionally, there is increasing adoption of responsive loads (such as smart appliances) and energy management systems that manage those energy resources to maximize their value. To realize opportunities enabled by these technologies, markets and tariff structures are likely to evolve to realize and distribute the monetary value of these resources. If these structures do not evolve, new technologies, services, and use patterns are unlikely to be adopted [2]. Many market and tariff options are under consideration, including real-time retail pricing [3], critical peak pricing [4], aggregator control of DERs and participation in bulk markets [5], decoupling retail energy and capacity tariffs [6], transactive control systems [7], and others.

Combinations of tariff structures and technologies are likely to affect the timing of and total demand for electricity. Hence, the capability to model and test various combinations of tariff structures and technologies is useful to identify prime options before implementing these regulatory structures. Ideally, the models will link the performance of the loads and generation on the system, end-use decisions made by people or energy management systems, the physical performance of the distribution feeder, and the market structure driving operations for the consumer.

Others have developed tools and analyzed some aspects of this topic—but not all of them. Most analyses of the electricity system have focused on bulk power systems and have treated consumers as having a fixed load profile [8,9]. Analysis to support tariffs is usually not concerned with the potential benefits of demand-side management, so its potential to reduce grid expenses is neglected [10]. Analysis of the potential value of demand response to the bulk power system has primarily focused on estimating the value to the

system as a whole [11] with less attention on who realizes that value (i.e., the analyses do not identify how much of the savings goes to the system operator, various generators, homeowners, etc.). Such analysis does not commonly include the value of supporting the distribution system. Distributed PV hosting capacity limitations on distribution feeders have been analyzed, but those analyses have not included the potential impacts of storage if the tariff structure varies the price of electricity across time [12]. The “Value of Solar” has been analyzed for use in tariff development and includes basic impacts such as loss rates. However, those analyses usually have not explicitly included either additional effects on distribution feeders, such as peak load management on transformers, or the potential for storage and energy management systems to mitigate possible issues [13].

Analyses that include both the market and physical aspects of the distribution system often consider only immediate prices and ignore near-term price projections [14]. Including price projections can affect optimal load and storage profiles, as illustrated by results from a study of the impact of price-responsive residential thermostats on both the retail and wholesale markets [15] using the Agent-based Modeling of Electrical Systems (AMES) test bed with GridLAB-D [16]. A simple real-time pricing scenario, consisting of a cost adder to the wholesale price, was used. Custom code was developed to simulate and optimize the Heating, Ventilation and Air Conditioning (HVAC) system, based on a model predictive control approach, taking into account energy cost and occupant discomfort, as well as weather and price forecasts. However, the optimization is run only once a day, and is idealized in that it uses the same HVAC model for the optimization as for the simulation.

The National Renewable Energy Laboratory (NREL) is developing the Integrated Energy System Model (IESM) to analyze interactions between multiple technologies within various market and control structures to identify both financial and physical impacts on consumers and utilities. Physical impacts include both consumer comfort and distribution feeder operations such as voltage profiles and equipment maintenance needs. The IESM is intended to be used to identify barriers preventing new technologies from being fully utilized; inform regulatory, research and development (R&D), and deployment decisions; and provide market signals for hardware-in-the-loop (HIL) testing of technologies in NREL’s Energy Systems Integration Facility (ESIF). To this end, the IESM will perform detailed simulations of distribution and end-use technologies on a single feeder. In this paper, we describe the evolution of the IESM through its phased development.

The paper is organized as follows. Section 2 explains the SoS nature of any ESI solution. Section 3 provides an overview of the IESM and the various simulation tools that need to be brought together to conduct an experimental study in a computational environment. Section 4 describes IESM Phase I in detail, followed by the planned addition of HIL simulation study in IESM Phase II in Section 5. The IESM Phase II discussion also presents the enterprise

architecture that is required for conducting HIL experiments. Section 6 describes the simulation-only experimental case study and its results. Finally, some conclusions and a way forward are presented.

2. SYSTEM-OF-SYSTEMS (SOS) PERSPECTIVE

Any ESI solution, qualifies as a SoS [17]. Consider, for example, the electric “Smart Grid” with a high penetration of DERs that are managed independently, operated independently, manufactured by different vendors and have independent evolution life cycles, and are geographically displaced. These four characteristics existing together in any ESI solution classify it as an SoS. Bringing these systems together using advanced sensing, control, and communication technologies is a challenge in itself. This challenge is further compounded by the market component of ESI. In order to deploy ESI solutions, we need to further investigate another characteristic of SoS—the emergent behaviors—and ensure that the resulting SoS is reliable and delivers quality of both the service and power.

In ESI, the larger system is comprised of subsystems such as generation, transmission, distribution, load control, and communications. In these primary system categories, specialization occurs at the photo-voltaic (PV) farm level, power plant level, microgrid level, industrial/commercial level, retail level, consumer level, and finally at the smart-device level. NREL [18] has identified three ESI goals:

1. Integrate technologies into the system (Figure 1)
2. Integrate across functional layers (Figure 2)
3. Integrate across physical scales.

It is clear that any ESI solution encompasses the following six SoS characteristics [19,20]:

1. Managerial independence: The comprising systems are managed independently by various utility companies who own the power infrastructure components and by individuals who own the loads that convert energy into services such as light and heat.
2. Operational independence: The comprising systems are operated independently of other systems through various metrics and establishing operational criteria.
3. Evolutionary independence: Each of the comprising systems is continuously upgraded and has its own lifecycle.
4. Geographic displacement: An energy system in general is geographically displaced. Introducing new smart components at the edge of the SoS (at the consumer level) adds more definition to the geographic displacement.
5. Emergent behavior: The behaviors that result through the interaction of a large number of components in real-time may be benign or harmful to the ESI ecosystem. With the addition of prosumers, capable of storing and generating energy along with consuming it [21], such behaviors have not yet been correctly identified.

6. Purpose: The goals of the ESI SoS, to name a few, include:
 1. Reduced energy use and expense
 2. Increased integration of distributed generation
 3. Reduce probability of outages
 4. Real-time management and control of various prosumers
 5. Improved utilization of components allowing for reduced overbuilding of systems (capital sitting)
 6. Enabling consumers to use energy systems based on their values and needs (e.g., "green" electricity).

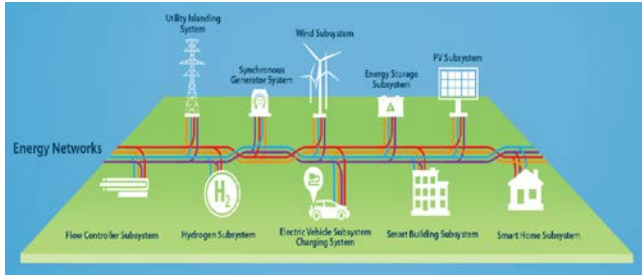


Figure 1. Integrate technologies in ESI [18]

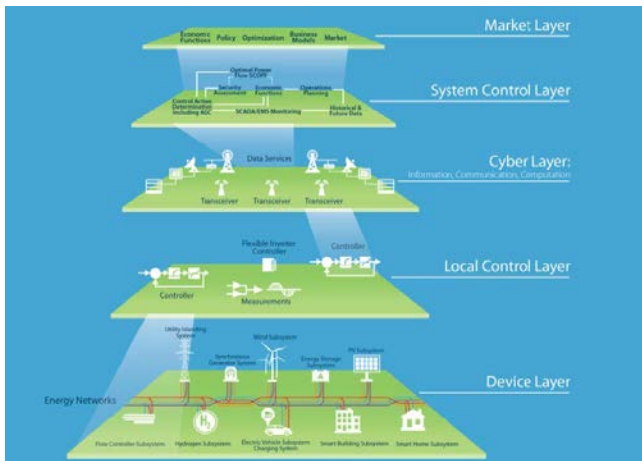


Figure 2. Integrate across functional layers [18]

Along with these principal characteristics, the other two key enablers for architecting an ESI solution are interoperability and real-time aspects. To further this cause, the Smart Grid Interoperability Panel (SGIP) [22] is developing various standards to facilitate data interoperability. Much progress is also being made in the area of Big Data and real-time analytics [23] that will eventually inform the cyber layer for such a SoS.

In order to create modeling and simulation (M&S) studies for ESI solutions, an enterprise software system M&S environment needs to be engineered that would allow testing various technologies in a lab setting incorporating HIL. With its IESM project, NREL is pushing for such a computational hardware-software system. This computational system involves assets including high-

performance computing (HPC) (i.e., the Peregrine supercomputer at the ESIF), the ESIF Smart Power Laboratory (SPL), and advanced distributed simulation infrastructure.

3. INTEGRATED ENERGY SYSTEMS MODEL

3.1. Overview

The IESM M&S environment integrates the GridLAB-D power system simulator that also models houses and appliances, with home energy management system (HEMS) optimization technologies. The IESM has evolved through two phases. The first phase is a proof-of concept that implements a discrete time M&S software environment on an HPC platform. The second phase is a hardware-software integration exercise that integrates hardware assets with the discrete event M&S enterprise environment using HPC-enabled HIL.

The IESM uses GridLAB-D's endogenous load models and simulation of distribution feeder performance. It is linked to multiple instances of HEMS simulations that optimize the operation of thermostats. The co-simulation structure manages timing and data transfer between the components.

While Phase I utilizes the GridLAB-D scheduler, Phase II utilizes an external discrete event scheduler that operates on abstract time, implemented using the Discrete Event Systems (DEVS) formalism [24]. The scheduler is expected to manage GridLAB-D's simulation of distribution feeders; simulation of loads and DERs either in GridLAB-D [25] or another simulation package such as Energy Plus [26]; simulation of HEMS technologies and markets; actual air conditioning hardware in SPL; and an agent-based model of the consumers' selections that may involve both preferences and learning.

3.2. GridLAB-D

GridLAB-D is a power distribution system simulation tool developed by Pacific Northwest National Laboratory (PNNL). It performs quasi-steady-state solutions for distribution feeders and uses agent-based methods to simulate end-use loads in appliances, heating-cooling systems, and other equipment. It also provides retail market modeling tools including price-responsive end-use loads.

A simple GridLAB-D model was created in order to illustrate the existing co-simulation capabilities of the IESM. The IEEE 4-node test system available as a model within GridLAB-D [25] was modified by: 1) reducing the line length in order to reduce the voltage drop across lines 3- and 4, and 2) adding a split-phase transformer to node 4, and loading the transformer with three houses, as shown in Figure 3. For larger simulations, house models will be created based on scripts developed by PNNL and Pinney [27].

Cooling loads are calculated endogenously based on the houses' sizes, insulation levels, window types, cooling systems and performance thereof, weather conditions, and thermostat set points. Likewise, water-heating loads are calculated endogenously. All other loads are modeled as a

ZIP load with its load-curve based on fitting to simulated loads (for lights, range, dishwasher, refrigerator, freezer, microwave, clothes washer and dryer, and miscellaneous plug-loads) set to “implicit” in GridLAB-D but reduced moderately.

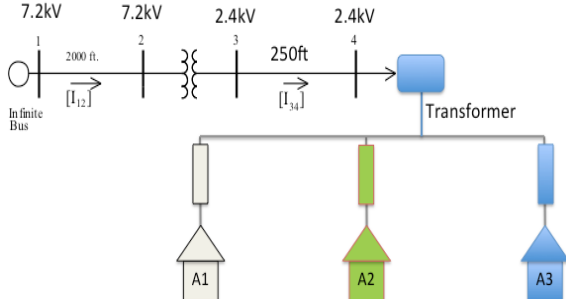


Figure 3. Modified IEEE 4-node system. Three identical houses are added behind a 25 kVA transformer, and length between nodes 3 and 4 is reduced to 250 ft.

3.3. HEMS: Optimization Engine

The current instantiation of the IESM includes a simulated HEMS for each house that minimizes the house’s cooling cost. In the future, the HEMS model will be expanded to one that can perform multi-objective optimization [28] and coordinate the operation of multiple household appliances including an electric water heater, electric vehicle, home energy storage system, dishwasher, and washer-dryer [29]. The HEMS uses a model predictive control approach [30,31] and sets the cooling setpoint θ_t^{set} to a calculated optimal value.

The HEMS optimizes for electricity cost for cooling with a comfort constraint that is specified as an envelope around the desired temperature. Specifically, the maximum setpoint is set to 2°F warmer and the minimum setpoint is set to 4°F cooler than the desired temperature at all times. To determine the minimum cost, we utilize a linear program that minimizes cost.

$$C = \sum_{t=1}^{NT} p_t \lambda_t T \quad (1)$$

where C is the total cost over N time periods of duration T and p_t and λ_t are the air conditioner’s load and electricity price for the time period t , respectively. The minimization is subject to the following constraints:

$$0 \leq p_t \leq p_{max} \quad (2)$$

$$\theta_t^{min} \leq \theta_t \leq \theta_t^{max} \quad (3)$$

$$\theta_t = \alpha_1 \theta_{t-1} + \alpha_2 p_t + \alpha_3 \theta_t^{out} \quad (4)$$

where p_{max} is the power rating of the cooling system, θ_t is the indoor air temperature for time period t , θ_t^{min} is the minimum allowable setpoint, θ_t^{max} is the maximum allowable setpoint, and θ_t^{out} is the outdoor air temperature. The cooling setpoint is set equal to the optimal indoor air temperature determined by the HEMS, i.e., $\theta_t^{set} = \theta_t$. A linear regression is performed on GridLAB-D data for each house without an intercept and with no feature scaling in order to determine the coefficients α_1 , α_2 and α_3 [28,31].

In the example below, the horizon for each optimization is 24 hours and optimal setpoint schedules are updated hourly, i.e., T is 1 hour and N is 24. Thus, the optimization uses a one-day window.

4. IESM PHASE I

As stated earlier, Phase I is the software instantiation used for the case study (see Section 6) and incorporates running the simulation on an HPC system. The co-simulation system links the GridLAB-D and HEMS executions through management of both time and data exchange through a discrete-time scheduler. HEMS optimization engine is wrapped within a HEMS controller that interfaces with GridLAB-D. It requires both of the components to exchange data:

1. House n Data: Outside temperature, indoor air temperature, desired temperature, and price signal
2. House n Setpoint: Cooling setpoint.

4.1. System/Component Structure

Several application programming interfaces (APIs) were developed to configure the distribution feeder, components including appliances and houses, and market structures within the single *.glm* file used for input to GridLAB-D. These APIs reduce error and enable increased complexity in the *.glm* files. The APIs also generate setup files, with specific start and end times, and coordinate execution with various software components implemented in the co-simulation system. Using these tools, it is relatively straightforward to visually inspect how the components, or a subset of the components, are connected in the graph. Figure 4 shows the basic components and APIs implemented in the IESM prototype.

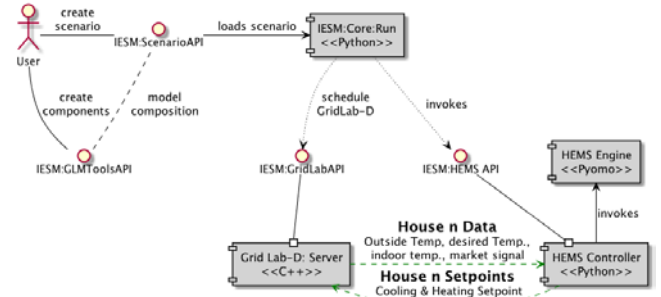


Figure 4. IESM Phase I UML Component diagram.

4.2. System Behavior

After the scenario is composed, but before simulation, the discrete-time scheduler (IESM:Core) generates the data (in *.csv* format) for the entire simulation period and the house datasets that are used by their respective HEMS for model-predictive control. During simulation, time is managed by the IESM:Core component. It begins the GridLAB-D simulation for the entire duration and invokes the HEMS every hour of simulation time. Because the HEMS has no strict time requirements, it acts as a proxy-slave. HEMS engine is implemented in Pyomo [32]. The HEMS is the

most computationally intensive component of the IESM model, so GridLAB-D, after simulating each hour, waits for the HEMS before continuing its simulation. Because each house has corresponding HEMS that requires significant computational time (from wall-clock seconds to minutes), HEMS engines were executed in parallel on an HPC platform. Once the HEMS have generated the cooling setpoints, they are collated for use in GridLAB-D. Data is exchanged when the simulation control is passed from the GridLAB-D Server (IESM:Bus component) to the HEMS controllers, and vice versa. The simulation execution process and the associated data exchange between GridLAB-D and HEMS (for 1...n houses) is shown through a UML Sequence diagram [33] in Figure 5.

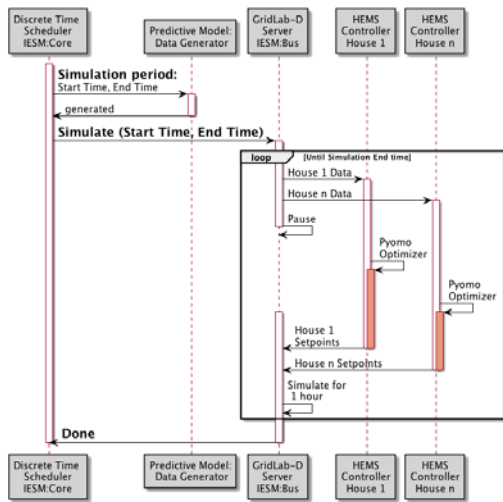


Figure 5. IESM Phase I co-simulation UML Sequence diagram.

5. IESM PHASE II WITH HARDWARE-IN-THE-LOOP

With Phase I of the IESM project completed, Phase II advanced towards integrating real hardware in the ESIF SPL and HPC M&S environment. The M&S environment, which made synchronous calls in Phase I, was made asynchronous due to the requirements of the real-time components. Consequently, the M&S architecture was adapted to account for asynchronous messages, discrete event invocations, hardware control, and real-time execution.

The hardware-software co-simulation exercise fulfills the following objectives:

1. Utilize model-based systems engineering (MBSE) principles [24,34] to ensure the component system's behaviors and their modeling are in synchronization.
2. Transform the developed control and communication enterprise architecture as an ESI solution.
3. Identify the standardized data types for interoperability considerations.

The first objective is ensured by the DEVS formalism that is founded on mathematical Systems Theory. This allows the development of a behavioral state machine for each component and guarantees that each component is in the desired state at the required time in relation to other components of the system. Consequently, complex dynamical behavior can be verified.

The second objective is achieved by the development of a netcentric enterprise SoS [34] that involves the following components: Air conditioner (A/C) and Nest thermostat hardware, message queues, an HPC platform, and M&S software using both wired and wireless networks. Integration between various components is performed either using direct network-socket calls or web-service calls with defined data-types (per the third objective above) as is required in any Service-Oriented Architecture (SOA).

In performing Systems M&S, we have to first describe the system per Systems Theory which requires the description of both the structure and behavior of the system under study. In this study, the prime executable components are GridLAB-D, the HEMS engines, and A/C and Nest thermostat hardware. The behavior of GridLAB-D and the HEMS engine were wrapped in DEVS state machines, and the hardware execution was wrapped in other software APIs callable from the DEVS state machines. As of writing this article, hardware integration testing at SPL has been performed successfully for a full 24 hour real-time operation using various APIs in the operational architecture described below. Efforts are underway for a more realistic HIL scenario for a month duration. The simulation results shown ahead are without HWIL for a two week scenario.

5.1. System Structure

The Phase II component diagram is shown in Figure 6. It is broadly divided into three prime components: the HPC system (Peregrine), wireless NEST thermostat API accessible through public Internet, and SPL.

The HPC environment is expected to host: the market layer within GridLAB-D, the HEMS optimization engines executed in parallel, the GridLAB-D simulator in server mode and various Python APIs to interface these components, and the DEVS controller to synchronize behavior between the components. In Figure 6, green arrows depict read operations, red depict read-write operations, and blue depict control signals. It should be noted that the entire experiment (briefly described in Figure 3) is executed in GridLAB-D, and only one air conditioner model in one of the houses has been replaced with the actual A/C system in the SPL controlled through Energy Plus. The hierarchical model is best described by the System Entity Structure (SES) [24,34] that illustrates the available design choices (Figure 7). The greyed entities reflect the selected configuration in the house design-space. As shown, the air conditioner and NEST thermostat are the only hardware components. The other appliances are software loads implemented in the GridLab-D house model.

IESM Co-Simulation Component Architecture (Phase II, Version 2)

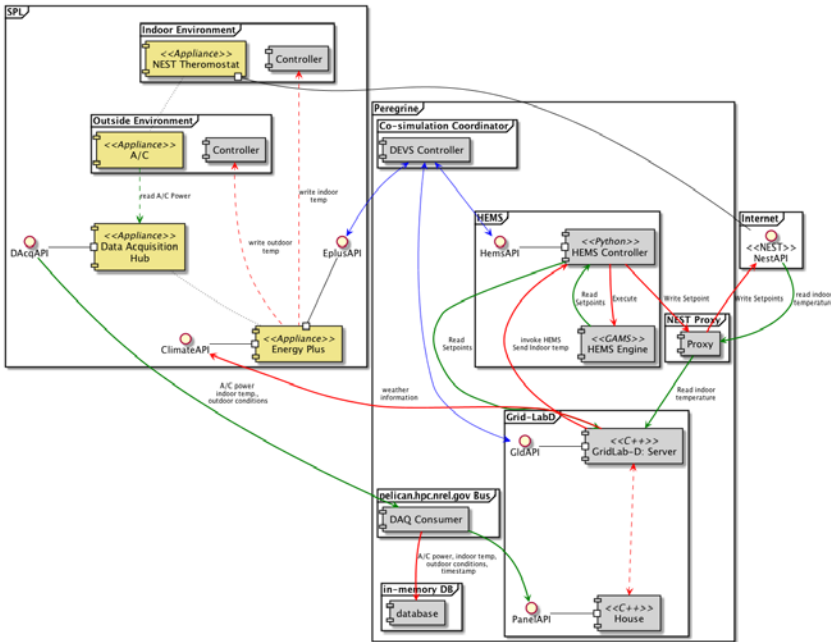


Figure 6. System deployment diagram involving the HPC (Peregrine) and SPL at NREL's ESIF. Blue arrows mean control signals, red arrows mean read-write signals and green arrows mean read signals

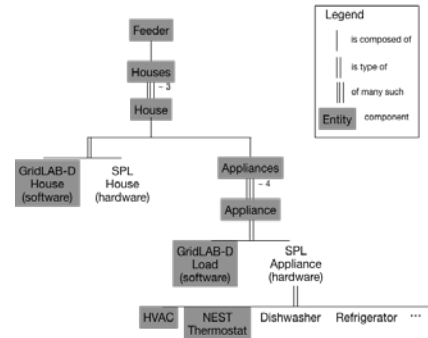


Figure 7. System Entity Structure (SES) diagram for IESM case study.

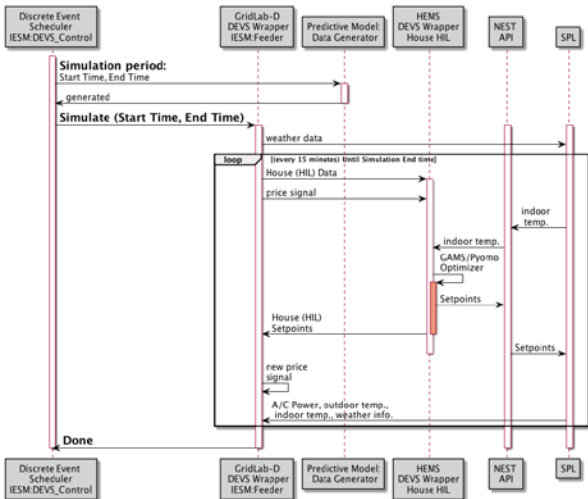


Figure 8. UML Sequence diagram showing interaction between various IESM components (hardware/software)

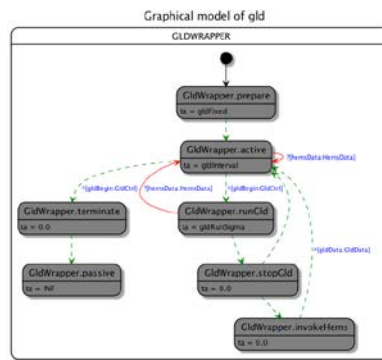


Figure 9. DEVS wrapper controller for GridLAB-D simulator component

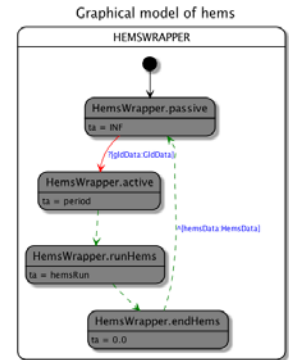


Figure 10. DEVS wrapper controller for HEMS engine component.

5.2. System Behavior

The system behavior of various interacting components is described using an UML Sequence diagram (Figure 8) and the DEVS state machine for GridLab-D (Figure 9) and the HEMS controller (Figure 10). Each of the components is running in their own threads asynchronously. Providing further details on the systems' behavior is outside the scope of this paper.

5.3. Real-Time and Virtual-Time Considerations

Having described the modeling aspect of the system, we now focus on the simulation execution aspect. The dynamic behavior of a complex system can only be ensured when each of the components is running on the same time-base (i.e., each component advances its clock simultaneously). This is a critical issue in distributed systems M&S where each of the components may be managerially and operationally independent and act as a black-box providing no external control over their time-base. This becomes more problematic when it is unknown whether the

component is simulating using discrete-time, discrete-event, or a hybrid. When the simulation is executed in real-time (i.e., the components execute in sync with the wall-clock time), the time-base is the same. Apparently, no top-level coordinator is required to synchronize the time-base. However, if the network delay is significant, various synchronization strategies (e.g., optimistic vs. conservative) [35] need to be applied to ensure timely delivery of messages. In the case of virtual time (i.e., as-fast-as-possible mode), it is imperative to have a top-level coordinator to synchronize the time-base of each of the components so that events can be exchanged in a timely manner. Running a distributed simulation in virtual time is much easier, as the network delay can be incorporated as “processing time” and factored in by the root coordinator. The solution to the above issues is to implement a root coordinator in abstract time that can be tuned to real time for any real-time studies.

5.4. Complex Dynamical Discrete Event System

IESM employs a distributed real-time discrete event M&S paradigm. The simulation layer of the enterprise M&S environment can be implemented in two ways:

1. A software engineering approach that implements a time-ordered event-queue. Each component interfaces with this global event-queue.
2. A systems engineering approach that implements closure-under-coupling property ensuring that events are transmitted to the designated destinations and concurrency is accurately implemented. Each component model implements its own event-queue and event-exchange happens through a coupling specification. The closure-under-coupling property guarantees the weak emergent behavior in any complex system M&S [36].

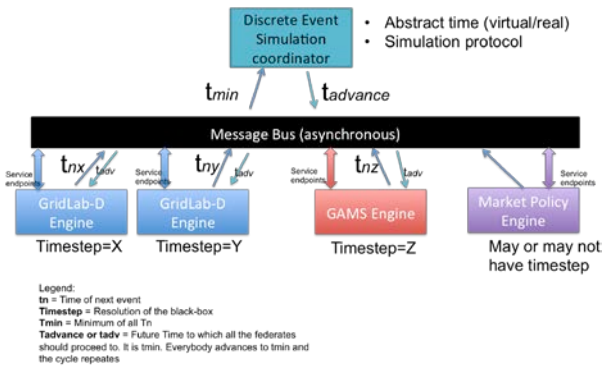


Figure 11. DEVS Coordinator in abstract time.

In our implementation, as we subscribe to Systems Theory for our M&S environment, we adopt the DEVS formalism, as it is founded on similar principles. The DEVS formalism categorically separates a model and its simulator through a layered architecture [24,37]. It specifies a simulation protocol between the model and its respective simulator. The simulation layer implementing the protocol coordinates

these component-simulators, ensuring *legitimacy* [24]. The DEVS formalism is based on complex dynamical systems theory. In a dynamical system, we are concerned with two aspects: the next state, and the time to next state from the current state. Consequently, a DEVS model implements a state-space, the explicit time specification between the states, and various transition functions that are triggered as events are received during the time-to-transition to the next state, thereby capturing the “elapsed time” between the two states. Theoretically, a DEVS system is an infinite-state system, as the time between two states is a floating-point number. An in-depth discussion of this topic is available in [24]. For our enterprise ESI M&S environment, Figure 11 depicts the simulation layer. Various simulation components (i.e. GridLab-D, HEMS, market engine, etc.) are wrapped in DEVS models (Figures 7 and 8). The DEVS coordinator implementing the DEVS simulation protocol interacts with these wrappers through a netcentric enterprise message bus, ensuring the advance of time and behavior of each of the component simulators.

6. CASE STUDY

6.1. Power System in Consideration

An example case in simulation-only mode, i.e. no HIL, was run to illustrate the ability of the IESM to evaluate the potential impacts and benefits of HEMS technology with a time-of-use tariff. Three identical houses were added to the IEEE 4-node test system described in Section 3.2. The houses are well-insulated, 2480-square-foot, single-story, single-family homes with air conditioners rated at 30000 Btu/h.

Weather conditions for North Carolina were used, and all three homes are subjected to Duke’s North Carolina pilot residential time-of-use electricity rate structure. That structure has two rates: an on-peak (noon to 6 p.m.) rate of \$0.152393/kWh and an off-peak (6 p.m. to noon) rate of \$0.072619/kWh [38]. The total bill for all scenarios includes a \$10/month service fee.

Each of the three identical homes has a unique desired cooling temperature profile. House A1’s desired temperature profile is 75°F at 6 a.m. and remains there until 10 p.m. when it is set to 79°F for the night. House A2’s desired temperature profile is motivated by the EPA Energy Star recommendations [39] and is 75°F at 6 a.m.; 80°F at 8 a.m.; 75°F at 6 p.m.; and 79°F at 10 p.m. House A3’s desired temperature is constant at 75°F at all times.

6.2. Results

Co-simulation results for houses A1, A2, and A3 for one July day are displayed in Figs. 12–14. In each figure, results with HEMS are compared to operations without HEMS, where the thermostat is set to the desired temperature according to the schedule above for a single day. The shaded area indicates when the electricity price is high as described above. The dashed lines indicate the minimum and maximum allowable temperature setpoint for each house. The time-varying lines show the desired

temperature, air temperature without HEMS, HEMS setpoint, and air temperature with HEMS.

House A1's HEMS minimizes cost by pre-cooling before the price increase, as shown in Figure 12. It increases at noon by reducing the setpoint from the desired temperature of 75°F to about 72°F between 8 a.m. and noon. The setpoint is then relaxed and the temperature allowed to increase during the on-peak time between noon and 6 p.m. With and without the HEMS, the air conditioner does not run during the nighttime hours when the desired temperature is 79°F. Over the period of July 7 – 17, utilizing the HEMS saves \$7 from the \$140 electricity bill without the HEMS, or 5% of the total bill including the service fee.

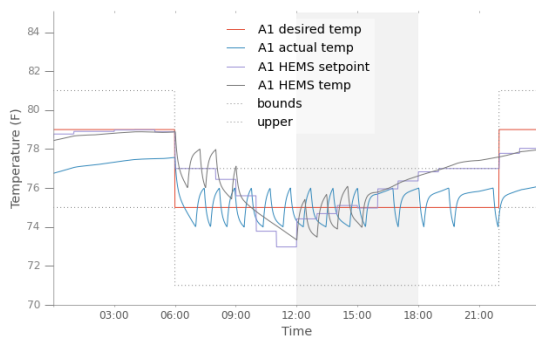


Figure 12. Co-simulation results for house A1 on July 9. The HEMS pre-cools the house a few hours before the higher time-of-use price period (noon to 6 p.m.).

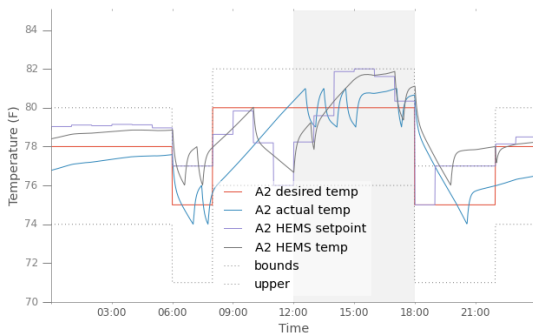


Figure 13. Co-simulation results for house A2 on July 9. The HEMS saves money by relaxing the setpoint during low-temperature hours (6 a.m.–8 a.m. and 6 p.m.–10 p.m.).

House A2's temperature profiles are shown in Figure 13. Like House A1, the HEMS minimizes cost by pre-cooling before the price increase at noon. The HEMS reduces the setpoint from the desired temperature of 80°F to about 77°F between 10 a.m. and noon so that the setpoint can be relaxed to the maximum allowable temperature of 82°F, and so the air conditioner does not run as much during on-peak pricing. After 6 p.m., the HEMS uses the maximum allowable setpoint, which is 2°F above the desired temperature of 75°F, to minimize cooling cost. As in House

A1, the air conditioner is not used at night due to the increased desired temperature. In the morning, the HEMS selects the highest allowable temperature of 77°F, as it did in the evening cooling period. Over the period of July 7 – 17, utilizing the HEMS again saves about 5% (\$7) from the \$129 electricity bill without the HEMS.

House A3's temperature profiles are shown in Figure 14. The HEMS reduces energy costs primarily by relaxing the setpoint to the maximum allowed temperature. Slight additional savings are achieved by precooling before the on-peak pricing period. Over the period of July 7 – 17, it is just a 3% reduction from the original \$140 bill without HEMS.

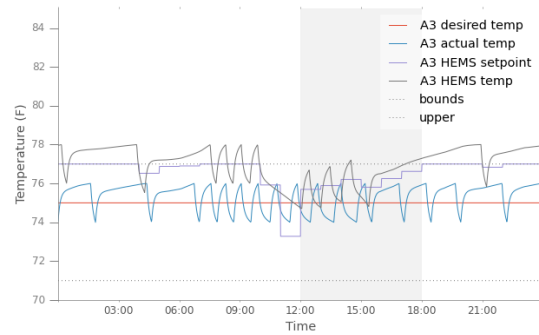


Figure 14. Co-simulation results for house A3 on July 9. The HEMS relaxes the setpoint throughout the day and pre-cools before the higher time-of-use price period (noon to 6 p.m.).

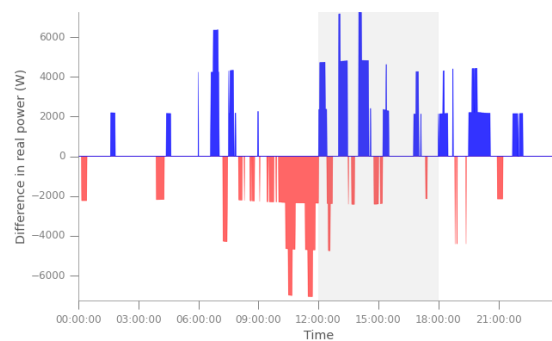


Figure 15. Impact of HEMS on transformer loading on July 9. Times shown in blue indicate when loading is higher without HEMS, and red indicates where the loading is higher with HEMS.

Figure 15 shows the differences in real power at the transformer feeding all three houses during the same day in July. As each house has the same non-cooling load, the difference calculation essentially represents the difference in air conditioner real power. The load shifts away from times when the cost of electricity is high (as shown in the shaded area) to times earlier in the day to precool houses, as discussed above. If the tariff is designed so that the increased rate corresponds with peak system load, utilizing the HEMS can help reduce the overall peak.

7. CONCLUSIONS

To better understand how new and evolving technologies—including distributed generation and storage, smart appliances, and energy management systems—integrate into the electrical grid and how tariff structures might drive operations, we simulate the effects of fully immersed technologies at scale using the IESM. The IESM uses co-simulation to integrate new technologies and markets with GridLAB-D power system simulation software. Currently, IESM includes HEMS technology for each house on a feeder, which minimizes cooling energy costs under comfort bounds by controlling the thermostat set points to realize cost savings.

Example results illustrate how the IESM can be used to evaluate a technology (in this case, HEMS) under a specific tariff (here, time-of-use). The HEMS described can provide 3%–5% savings on a home's full electricity bill during the month of July in North Carolina. The HEMS achieves these savings by precooling before the electricity price is increased to the on-peak rate and by allowing a higher temperature at other times. The combination of the HEMS and a time-of-use tariff structure may reduce the system peak by reducing air conditioning during peak hours.

We described the phased development of the IESM with Phase I purely in the software domain and Phase II adding HIL. We discussed the development of a discrete event enterprise M&S environment in Phase II as a requisite to real-time HIL testing and evaluation. Incorporating the SoS concept and Systems Theory provides value to the parallel distributed enterprise M&S environment that can be scaled to a more complex feeder configuration and a large number of houses using HPC resources. Any ESI solution manifests the six characteristics of an SoS approach. While we have evidence of managerial, operational, evolutionary, and geographical independence, the subject of emergent behavior needs to be investigated in detail through a much more elaborate case study with a large number of components and interactions. This article described the computational environment needed to realize ESI goals (Figures 1 and 2).

In future work with the IESM, we intend to add components controlled by the HEMS, simulate full distribution feeders, investigate the performance of components under additional market structures, and implement HIL testing capabilities. Additional components such as electric vehicles, water heaters, home energy storage systems, and appliances such as dishwashers and washer-dryers will be included to test the additional impacts and cost savings potential of controlling multiple loads. We also plan to investigate other rate options, including real-time pricing generated within a linked distribution-bulk power simulation. We also plan to investigate services (e.g. gas, water, thermal) beyond electricity and how they might be valued based on topographic location of feeders.

ACKNOWLEDGEMENTS

This work is supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Laboratory Directed Research and Development funding at the National Renewable Energy Laboratory, under contract DE-AC36-08GO28308.

REFERENCES

1. M. Ruth, B. Kroposki, "Energy Systems Integration: An evolving energy paradigm," *Electr., J.*, 2014, DOI: <http://dx.doi.org/10.1016/j.tej.2014.06.001>
2. Electricity Innovation Lab – Rocky Mountain Institute "New business models for the distribution edge the transition from value chain to value constellation," Apr. 2013.
3. H. Alcott, "Rethinking real-time electricity pricing," *Resource and Energy Economics*, vol. 33, pp. 820-842, Nov 2011.
4. K. Herter, "Residential implementation of critical-peak pricing of electricity," *Energy Policy*, vol. 35, pp. 2121-2130, Apr. 2007.
5. S. Barsali, M. Ceraolo, R. Giglioli, D. Poli, "Aggregation and management of the demand in a deregulated electricity market," *Power Tech Conference Proceedings, 2003 IEEE Bologna*, vol. 4, 23-26 June 2003.
6. Electric Power Research Institute, "The integrated grid realizing the full value of central and distributed energy resources," Electric Power Research Inst., Palo Alto, CA, Tech. Rep. 3002002733, Feb. 2014.
7. A. Ipakchi, "Demand side and distributed resource management — A transactive solution," *2011 IEEE Power and Energy Society General Meeting*, pp. 1-8, 24-29 July 2011, doi: 10.1109/PES.2011.6039272.
8. D. Lew, G. Brinkman, E. Ibanez, A. Florita, M. Heaney, B.-M. Hodge, M. Hummon, G. Stark, J. King, S.A. Lefton, N. Kumar, D. Agan, G. Jordan, S. Venkataraman, "The western wind and solar integration study phase 2," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/TP-5500-55588, Sept. 2013.
9. D. Corbus, M. Milligan, E. Ela, M. Schuerger, B. Zavadil, "Eastern wind integration and transmission study – preliminary findings," National Renewable Energy Laboratory, Golden, CO, Conf. Paper NREL/CP-550-46505, Sept. 2009.
10. D.S. Kirschen, "Demand-side view of electricity markets," *IEEE Trans. on Power Systems*, vol. 18, pp. 520-527, May 2003.
11. M. Hummon, et al, "Grid integration of aggregated demand response, part 2: modeling demand response in a production cost model," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/TP-6A20-58492, Dec. 2013.

12. J. Smith, "Stochastic analysis to determine feeder hosting capacity for distributed solar PV," Electric Power Research Inst., Palo Alto, CA, Tech. Rep. 1026640, Dec. 2012.
13. P. Denholm, R. Margolis, B. Palmintier, C. Barrows, E. Ibanez, L. Bird, J. Zuboy, "Methods for analyzing the benefits and costs of distributed photovoltaic generation to the U.S. electric utility system," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/TP-6A20-62447, Sept. 2014.
14. D.J. Hammerstrom, et al, "Pacific Northwest GridWise testbed demonstration projects part I. Olympic Peninsula project," Pacific Northwest National Laboratory, Richland, WA, Tech. Rep. PNNL-17167, Oct. 2007.
15. A.G. Thomas, C. Cai, D. C. Aliprantis and L. Tesfatsion, 2012, "Effects of Price-Responsive Residential Demand on Retail and Wholesale Power Market Operations," IEEE PES General Meeting.
16. D. P. Chassin, K. Schneider, and C. Gerkenmeyer, 2008, "GridLAB-D: An opensource power systems modeling and simulation environment," Transmission and Distribution Conference and Exposition, 2008.
17. J. Perez, J. Diaz, J. Gargjosa, A Yague, E Gonzalez, M. Lopez-Perea, "Large-scale Smart Grids as System of Systems,, First International Workshop on Software Engineering for System-of-Systems, 2013.
18. B. Hannegan, "Energy Systems Integration," National Renewable Energy Lab, 2014. Available at: http://energy.gov/sites/prod/files/2014/01/f7/fupwg_winter2014_hannegan_0.pdf. Accessed March 20, 2015.
19. M. Maier, "Principles of System of System Architecture," 1998.
20. S. Mittal, "Model Engineering for Cyber Complex Adaptive Systems," Workshop on Model Engineering, European Modeling and Simulation Symposium, 2014.
21. S. Grijalva and M. U. Tariq, "Prosumer-based smart grid architecture enables a flat, sustainable electricity industry," presented at the IEEE PES Innov. Smart Grid Technol. Conf. (ISGT), Hilton Anaheim, CA, Jan. 17–19, 2011.
22. Smart Grid Interoperability Panel, accessible at www.sgip.org.
23. P. Russom, "Big Data Analytics", TDWI Best Practices Report, 2011
24. B.P. Zeigler, H. Praehofer, T.G. Kim, "Theory of Discrete Event Modeling and Simulation," Academic Press, 2000.
25. D. P. Chassin, K. Schneider, C. Gerkenmeyer, "GridLAB-D: An open-source power systems modeling and simulation environment," *IEEE/PES Transmission and Distribution Conference and Exposition, 2008*, pp.1-5, 21-24 April 2008.
26. D.B. Crawley, L.K. Lawrie, C.O. Pederson, F.C. Winkelmann, "EnergyPlus: energy simulation program," *ASHRAE Journal*, vol. 42, pp. 49-56, Apr. 2000.
27. D. Pinney, "Costs and benefits of conservation voltage reduction CVR warrants careful examination," National Rural Electric Cooperative Association, Arlington, VA, Tech. Rep. DE-OE0000222, Nov. 2013.
28. A. Pratt, B. Banerjee, T. Nemarundwe, "Proof-of-concept home energy management system autonomously controlling space heating," *Power and Energy Society General Meeting (PES), 2013*, July 2013.
29. A. Brissette, A. Hoke, D. Maksimovic, A. Pratt, "A microgrid modeling and simulation platform for system evaluation on a range of time scales," in *Proc. IEEE Energy Conversion Congress and Exposition*, Phoenix, Arizona, USA, 2011.
30. J.B. Rawlings, "Tutorial overview of model predictive control," *IEEE Trans. Control Systems*, vol. 20, no. 3, pp. 38-52, 2000.
31. C.D. Corbin, G.P. Henze, P. May-Ostendorp, "A model predictive control optimization environment for real-time commercial building application," *Journal of Building Performance Simulation*, Jan 2012.
32. <http://software.sandia.gov/trac/pyomo/wiki/Pyomo>. Accessed November 29, 2014.
33. <http://www.ibm.com/developerworks/rational/library/3101.html>. Accessed December 1, 2014.
34. S. Mittal and J.L.R. Martin, "Netcentric System of Systems Engineering with DEVS Unified Process," Boca Raton, FL, 2013.
35. R. Fujimoto, "Parallel and Distributed Simulation Systems," Wiley-Interscience, 2000.
36. S. Mittal, "Emergence in Stigmergic and Complex Adaptive Systems: A Formal Discrete Events Perspective," *Journal of Cognitive Systems Research*, 2013.
37. S. Mittal, B.P. Zeigler, J.L.R. Martin, F. Sahin, M. Jamshidi, "Modeling and Simulation for System of Systems Engineering," in *System of Systems Engineering for the 21st Century*, ed. Mo Jamshidi, 2008.
38. http://www.duke-energy.com/tou-nc-residential/rate_comparison.asp. Accessed November 26, 2014.
39. http://www.energystar.gov/ia/partners/prod_development/revisions/downloads/thermostats/ProgramThermDraftI.pdf?0b55-1475. Accessed November 29, 2014.