21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2014 Grid of the Future Symposium

A Benefit-Cost Framework for Optimal Load Shifting*

R. SKORUPSKI[1†], L. HU[2] . R. ENTRIKEN[3], Y. YE[1†]
[1]Stanford University
[2]University of California at Berkeley
[3]EPRI
United States

SUMMARY

We describe the background and analytical framework for a mathematical optimization model for home energy management systems (HEMS) to efficiently shift electricity load. We illustrate the flexibility of the model by modularizing various available technologies such as plug-in electrical vehicle, battery storage, automatic window opening, etc. The analysis shows that the end user can accrue economic benefits by shifting consumer loads away from higher-priced periods. Our simulation findings based on real or generated data enhance the motivation for more intelligent electricity management in the residential sector, and they demonstrate that our HEMS model can accrue substantial benefits by applying the process of load shifting to further flatten the baseline electricity load shapes of a particular household. Therefore, wide adoption of such a model could create significant cost savings for consumers. We also discuss the major concerns associated with the model use in the real world, and the possible future avenues of research investigation.

KEYWORDS
Home Energy Management Systems
Smart Grid
Demand Response

* This research is supported in part by the Precourt Energy Efficiency Center, Stanford University. This material is based upon work supported by the Department of Energy under Award Number DE=EE=0002628.

[†]This author is also partially supported by the Major Program of National Science Foundation of China [Grant 71320107001].

[†††]ryan.skorupski@alumni.stanford.edu

1. Introduction

The motive for this research is to help determine the most likely sources of value to be derived from smart grid technologies. These technologies involve the addition of automated decision support for energy consumption and the potential for tight integration of communication networks and for effective coordination of energy production and consumption [2][11].

1.1 Demand Response

One solution that can accommodate the needs of the electric grid system when there is a mismatch between electricity supply and consumer demand is Demand Response (DR), which addresses this concern by controlling system loads in such a way that reduces the differential between electricity supply and demand [2][6].

In the United States, the market for DR programs is already prevalent and mature in the commercial and industrial sectors with the presence of third-party providers [8]. Market actors utilize programs involving interruptible loads, direct load control, real-time pricing, and time-of-use programs [4][10].

In contrast, the market for DR programs in the residential sector is currently in a nascent stage [6]. The majority of DR programs in the residential sector consist of a type of direct load control program for water heaters. The remaining are pricing programs of the following types: time-of-use, critical peak pricing, and day-ahead pricing [1].

Because these DR programs are not widely used in the residential sector, the paper will focus on load shifting for the residential sector [8]. With the goal being to develop a framework for determining the sources of value that can help direct investment in residential demand response.

1.2 Economic Benefit

This paper focuses on the economic benefits attendant to residential load shifting that can be potentially accrued by participating consumers.

Currently, most utilities provide a pricing scheme with either two or three rates: 1) peak and off-peak; or 2) peak, semi-peak, and off-peak. Load shifting saves money under these schemes. Another pricing scheme that is less utilized is day-ahead pricing. This scheme provides a greater amount of changes in electricity prices over a given day and these prices are available from the utility a day ahead, which an intelligent algorithm can effectively exploit in terms of optimization [14]. There is also a greater economic interest to implement DR programs. Through their implementations, the utility may be able to manage an electricity supply shortage in a more expeditious manner with lower costs and less delay time.

1.3 Technology Background

To enhance the effectiveness of DR, the increasing integration of Information and Communication Technology (ICT) has enabled market actors to make technological advances in various fields. For example, in the field of energy management, ICT has engendered the smart grid, which enables the development of technologies and techniques such as the smart meter, bidirectional communication, advanced metering infrastructure (AMI), home automation, and home area networks [8].

An AMI, particularly the smart meter, serves the purpose of measuring and recording electrical energy consumption in time intervals that range from five minutes to an hour. It allows for two-way communication, either in real time or near real time, between the meter and the utility's system. The availability of such information would allow the consumer to modify consumption in order to shift electricity loads to times when energy is off peak and relatively cheaper. Moreover, the utility may receive information about the consumption patterns of its consumers and act accordingly to obtain economic benefits. For example, the utility can offer economic incentives to consumers who volunteer to shift electricity loads [3].

In the context of the increasing integration of ICT, a HEMS can be established in order to manage the use of energy in a household. As the development of smart grid technology continues, an intelligent HEMS can serve an important function in maximizing the economic savings associated with lower energy consumption and information sharing between consumers and their energy providers.

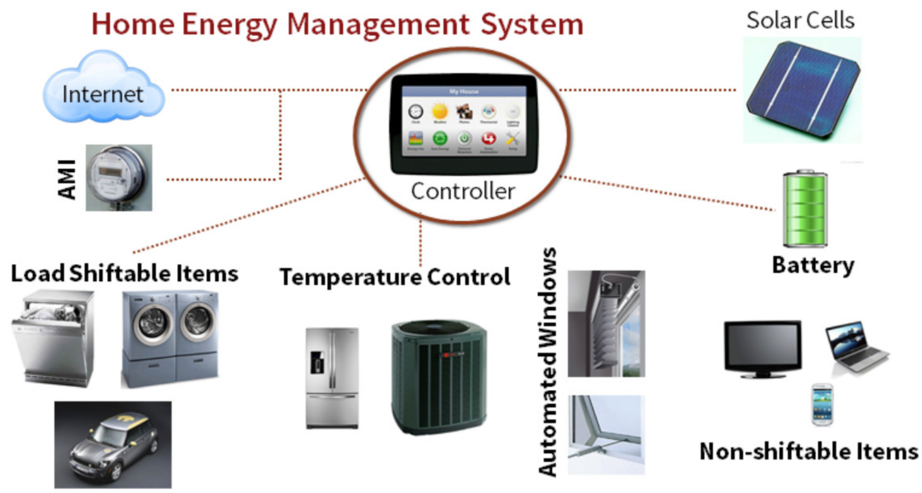

Figure 1: HEMS Diagram

Figure 1 illustrates a Home Energy Management System (HEMS) that offers monitoring and control of selected devices within a household [7]. The system itself can have varying levels of automation and intelligence [9]. As noted in Figure 1, the HEMS has a controller, which may be accessed directly or from any device that can connect to the Internet. Depending on the level of intelligence and automation, the controller would allow users to change certain preferences, such as the preferred run times for particular appliances.

1.4 Overview of the OLS Model

This paper describes a model that can be used by a HEMS to manage energy demand more efficiently. Our analysis demonstrates that a HEMS can accrue substantial benefits by applying the process of load shifting to effectively flatten the baseline electricity load shapes of a particular household. Therefore, wide adoption of such a model could create significant cost savings for consumers.

The main contributions of this research are:

1. OLS Model Formulation – a portfolio of techniques with scarcity enforced by a power usage cap and messaging between modules that indicate what information to communicate, to whom, and when,
2. OLS Cases – the construction of complete datasets that identify useful data sources and demonstrate the information necessary to complete such a study, and
3. Smart Grid Valuation Framework – simulations and comparisons of power usage over multiple cases pinpoint sources of value in the forms of
   - marginal values by appliance,
   - appliance portfolio effects under scarcity constraints, and
   - patterns of load shifting for higher-level modeling.

The implementation of the model shows that the end user can accrue economic benefits by shifting the consumption loads away from higher-priced periods. In the result's section, the precise savings are shown in addition to the load shift graphs. Furthermore, the model is capable of performing quickly, which is a highly preferred attribute of any algorithm that is designed to be implemented by a HEMS in real-time dynamic management.

These findings enhance the motivation for more intelligent electricity management in the residential sector. Companies that are interested in capitalizing in this developing market are encouraged to obtain further information about HEMS technology. In particular, we have demonstrated the flexibility of the model in the conclusion section under "Possible future investigation." Although the different scenarios tested were not exhaustive, they do show the model's capability of incorporating non-traditional motives — aside from those relating to electricity cost — into the objective function.

Following is a description of the analytical framework, which can utilize a model like OLS and others to evaluate critical questions about smart grid investments. Conclusions and next steps follow.

2. Smart Grid Analytical Framework

Five sets of case study results provide useful insights about the valid operation of the OLS model and how overall optimization of the HEMS can provide end-user savings. In this section we describe a framework to further aid in interpreting the OLS model results. The OLS model is a tool that provides a way to study the fundamental behaviors of a HEMS before and adding smart modules for various types of functionality, like load shifting, thermal controls, and battery storage. The Smart Grid Analytical Framework builds on the types of observations made possible by the OLS model to allow investigators to answer questions like:

- Which smart appliance provides the greatest overall savings?
- Which smart appliance provides the greatest incremental savings?
- Which smart appliance has the highest benefit/cost ratio?
- What incentives do smart appliances provide for behavioral changes?

In this section, we describe four analytical frameworks that can help answer these questions.

- *Smart Appliance Cost Analysis* - Compares actual appliance costs with and without communication and control abilities. This is useful for understanding the cost structure of smart appliances for investment purposes.
- *Smart Appliance Benefits Analysis* - Shows how to use the OLS model and cases to investigate appliance-level benefits. This is useful for understanding individual end user decision-making.
- *Smart Appliance Marginal Benefit Analysis* - Shows how to use the OLS model and cases to investigate the marginal benefits of individual appliances. This is useful for understanding the benefits of scale and the potential decisions of an aggregator or electric utility.
- *End-User Preference Sensitivity Analysis* - This is useful for understanding the value of various rate designs and their potential benefits to end users and other stakeholders.

The results in these sections were obtained from simulations using the five case study data sets. Each dataset represents a few days of operation in a typical week. While this is sufficient to show differences in benefits and costs among appliances, there is still much work needed to study much more realistic situations.

2.1 Smart Appliance Cost Analysis

This Smart Appliance Cost Analysis compares the costs of actual appliances for which there are comparable smart and non-smart versions. A smart appliance is one that has the ability to be remotely controlled, and recently companies have been introducing these kinds of smart household appliances. However, their offerings are still few in number. In the following, a company's smart appliance was compared in price to a company's most-similar model without the smart characteristic. Due to the current nature of the market for smart appliances, the models are all higher-end models. It was not possible to locate lower-tier models with smart characteristics at this time. Further, not all appliance providers have smart appliances in each category. For instance, there appears to be only one smart dishwasher as of April 2014.

The scatter plots in Figure 2 show appliance base prices versus the absolute difference (left plot) and percentage difference (right plot) between the smart and non-smart versions.

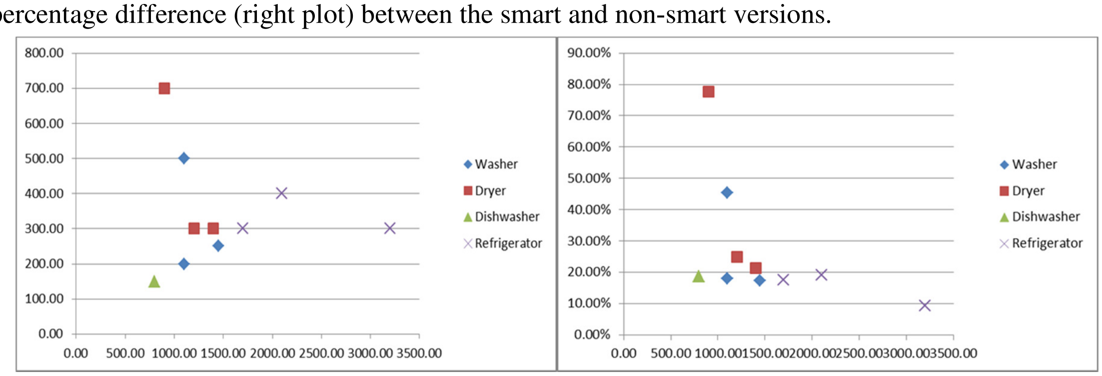

Figure 2: Base Price v. Abs. Difference and Base Price v. Per. Difference in dollars

At this time it is difficult to form a meaningful conclusion about the cost of something being smart, because of the infancy of the market and the dearth of smart household appliances, infrastructure, and incentives. Yet, the right plot does indicate a trend for smart appliance prices to have about a 20% markup. One refrigerator does have a lower (10%) markup, and one washer and one dryer have much higher markups of 50% and 80%, respectively.

Above, we examined the incremental cost associated with adding smarts to household appliances, but we did not investigate smart thermostats. It makes less sense to compare the price of a normal thermostat to a smart one, because almost every household already has a thermostat. When deciding whether to upgrade to a smart one, an end-user should look for the one with the lowest cost. As such, Table I contains the costs of the smart thermostats on the market, as of April 2014.

Table I: Smart thermostat costs, as of April 2014

Smart Thermostat	Cost
Nest 2nd Generation	\$250
Honeywell WiFi	\$202
ecobee Smart Si 01	\$200
Homewerks CT-30-H-K2	\$100
Allure EverSense	\$284

2.2 Smart Appliance Benefit Analysis

The Appliance Benefit Analysis investigates the average benefits of each appliance. This type of analysis can indicate incremental benefits by type of appliance, which can assist an end-user to understand the returns on investment from adding communication and controls to various types of appliances.

The benefit is calculated as the savings obtained from allowing each appliance's load to be shifted. Table II contains various measures of appliance benefits over the 7 days of Case 2: Springfield without Battery. The prices are much lower in the off-peak period, with a Day Ahead price range of [0.019, 0.04136] ¢/kWh.

Table II: Smart and Absolute Benefit of an Appliance

Appliance	Non-Smart Cost (\$/day)	Smart Cost (\$/day)	Savings (\$/day)	Savings (%)
Washer	0.0069	0.0042	0.0026	38.35
Dryer	0.0608	0.0385	0.0223	36.67
Dishwasher	0.0347	0.0222	0.0124	35.84
PEV	0.2194	0.1263	0.0931	42.45
HVAC	0.4253	0.1383	0.2870	67.47

Average costs (\$/day) are for each appliance over the 7-day model horizon. The Non-Smart column gives the average cost for the nominal load profile of each appliance. The Smart Cost column gives the average cost of operating the given appliance when its load is optimally shifted within the limits of the end user's preferences. The Savings (\$) benefit is the monetary value that was obtained by letting the given appliance load to shift. The Savings (%) is the percent change in Smart Cost relative to the Non-Smart Cost.

By examining these values for a given time frame, an end user can determine whether purchasing an appliance with load shifting ability would be worthwhile.

Assuming that the Savings (%) values are typical, or that typical values can be somehow computed with the OLS model, they can be used to compute the expected annual savings attributable to each appliance, given the average annual electricity cost for the appliance [13]. Table III contains the elements of such a calculation.

Table III: Annual Savings for an appliance

Applinace	Savings (%)	Average Annual Cost	Annual Savings
Washer	38.35	\$ 5.36	\$ 2.05
Dryer	36.67	\$ 71.40	\$ 26.18
Dishwasher	35.84	\$ 18.90	\$ 6.77
PEV	42.45	\$ 232.51	\$ 98.69
HVAC	67.47	\$ 108.00	\$ 72.87

The Savings (%) values are repeated from Table II, and the Average Annual Costs are from energy.gov [12]. Their differences for each appliance are in the Annual Savings column. With this annual savings value, an end user can compare this annual benefit with the annual amortized cost associated with adding communications and control (smarts) to the appliances and determine whether it makes economic sense to spend the extra money.

Combining the Annual Savings values in Table III with a few assumptions about the costs of smart appliances and thermostats, we arrive at the analysis in Table IV. We assume the following:

- The cost of making an appliance smart is an extra 20% on the purchase price.
- The nominal costs of non-smart versions of a washer, dryer, and dishwasher are given in the Table IV.
- The incremental cost of a smart charger is on the order of a smart meter, namely \$200.
- The incremental cost of a smart thermostat is about \$200, assuming that a homeowner would replace a good thermostats having no resale value.
- The payback period does not include a discount rate.

Table IV: Benefit-Cost Analysis for each appliance

Applinace	Non-Smart Cost	Incremental Cost	Annual Benefit	Payback Period
Washer	\$ 600	\$ 120	\$ 2	60 years
Dryer	\$ 300	\$ 60	\$ 26	2.3 years
Dishwasher	\$ 300	\$ 60	\$ 7	8.6 years
PEV Charger	\$ 2,000	\$ 200	\$ 99	2.0 years
HVAC	\$ 200	\$ 200	\$ 73	2.7 years

We can conclude from this table that adding smarts to the more energy intensive appliances, like the clothes dryer, the PEV charger and the HVAC system should provide a more robust benefit than a washer or dishwasher.

2.3 Smart Appliance Marginal Benefit Analysis

The following marginal benefit analysis is possible to implement for appliances that do not have defined load shapes, but are instead modeled as interactive with their environment and as having a limit on their capability. For this reason, we use the HVAC as the example appliance, and test the sensitivity of its benefits to changing kW capacity values.

Normally an end-user decision about the appropriate size of an HVAC system is specifically based on two factors: climate and house size, but with a HEMS, we can investigate the benefits derived from the ability of a larger HVAC system to pre-cool/pre-heat faster. This analysis leverages the Austin Pre-Cooling case, which increases the HVAC capacity from 2 to 12 kW, as shown in Table V. It uses the Day-Ahead pricing scheme from Austin Energy [5].

Table V: Case 5: Austin Pre-Cooling. Benefit of Increasing HVAC size

HVAC Capacity (kW)	2	3	4	6	8	10	12
Savings (%)	27.10	28.07	28.34	28.53	28.60	28.64	28.67
Savings ($)	0.78	0.81	0.82	0.82	0.82	0.82	0.83
Incremental Benefit ($)	n/a	0.0279	0.0078	0.0055	0.0020	0.0012	0.0009
Marginal Benefit ($/kW)	n/a	0.0279	0.0078	0.0028	0.0010	0.0006	0.0005

The benefit analysis in Table V shows that increasing the HVAC capacity has diminishing returns. Nevertheless, this framework shows how varying HVAC capacity can help to properly size the system.

2.4 Sensitivity on Resident's Behavior

The HEMS offers the end user the ability to choose the allowable periods of operation to which an appliance can be shifted. One question that logically arises is, "What is the cost or benefit associated with extending or curtailing the window of allowable operation?"

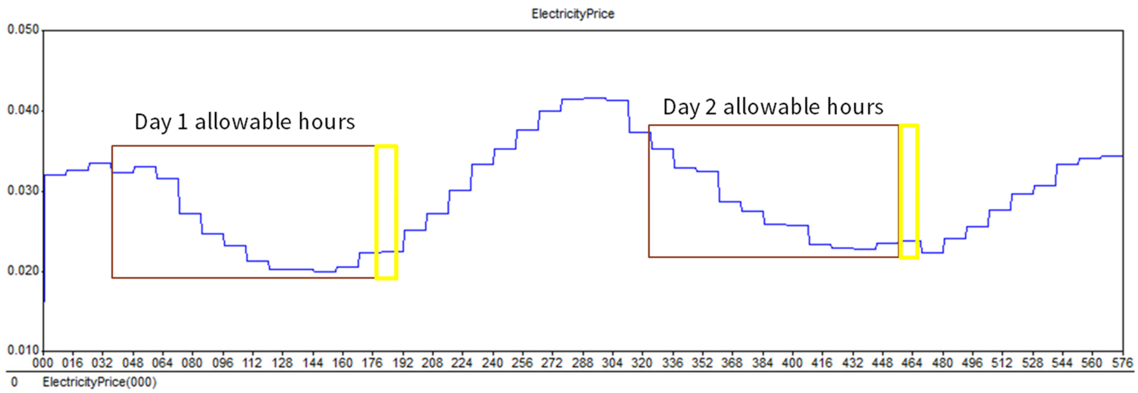

Figure 3: Extending Resident's Allowable Hours (kWh vs. time in 5-min intervals)

Testing this condition on the Springfield cases demonstrates that no benefit is obtained from lengthening the allowable period by an hour. This is because the allowable window of operation for the set of appliances that can be shifted already encompass the lowest price period, as seen in Figure 3. But this analysis is case-specific and may show interesting results for people with particular work schedules, and alternative cases must be tested to conduct such a cost-benefit analysis.

A similar sensitivity analysis on the settings of the allowable temperature range could also be done to determine the marginal benefit of expanding the range.

3. Conclusions

The OLS model has confirmed economic benefits for each of the five cases, and it has demonstrated its flexibility to configure its modules according to the circumstances. Therefore, existing modules can be improved as needed to represent further details of appliance use and additional modules can be added that better utilize user and electric utility preferences in order to enhance their mutually beneficial relationship. For most modules, the optimal load shifting solution time is less than a second, which makes the mathematical optimization model approach a viable technology to be implemented in practical and real time home energy management systems.

It is shown that the added capabilities of batteries and automated windows further improve end user benefits. The battery components can give extraordinary savings, but must be compared to its installation and maintenance costs and a utility's willingness to buy back electricity. Automated windows may provide benefits, but more scenarios must be tested to identify the best conditions for gaining them.

Further examining the results with the analysis framework leads to an understanding of whether current smart appliances are fairly priced. By installing a smart thermostat, the cost may be recouped within five years (based on Springfield). A 20% markup on dryers, washers, and dishwashers may not be recouped within five years, a reasonable appliance lifetime, based on the simulated savings. A PEV, which is a load-intensive appliance, may see significant savings from smart charging, but it is difficult to put a cost on that ability, because of the significant variations of installations and rapidly changing business landscape. Assuming a smart charger costs an extra $800, it may be worthwhile if the end user drives more than 30 miles a day, the approximate number of miles driven daily by the EV in our simulation, and has multiple electric vehicles; however, more scenarios must be simulated to validate such results.

3.1 Possible Future Investigation

Additional enhancements are made simpler, because of the model's modular design. First, the OLS model can be manipulated to handle non-concurrent and concurrent load shifting. This idea is particularly interesting for charging PEVs. It would be possible to accrue benefits from charging a fleet with overall supply capped for a limited time. In addition, a household might mitigate costs at a time when prices are volatile by not charging concurrently.

Furthermore, the OLS model can be modified to minimize or maximize other costs and benefits regarding the operation of a household or a utility; possibly a utility's ability to weigh a demand response option versus the cost of turning on an emergency generator.

Regarding the formulation, two avenues of future investigation easily arise. The first is to extend our current formulation, which is essentially a single zone, to multiple zones. This change allows us to explore added controls and more detailed modeling of the building. For example, heat exchanges between rooms can be modeled using fluid and thermal models. Furthermore, the behavior of the building's zones can be modeled using simulation programs and languages like EnergyPlus and Modelica. By turning off or rather utilizing less energy in certain zones within a building, we can explore possible added value to consumers, utilities, and third parties.

The second relates to the formulation of the automatic windows. Due to the slower run time associated with the automatic windows as performed now, we could create a two level approach to address when windows should open and close. This approach can be benchmarked with the current approach with the expectation of delivering a quicker solution.

Lastly, the model can provide insight into certain aspects of appliances and HVAC systems. A few ideas are:

- *Appliance Behavior* – Determine the most important factors affecting appliance behavior for purposes of forecasting sales and market penetration.
- *End User Behavior* – Determine the most important factors affecting end user behavior for purposes of characterizing how consumers can best benefit from the Smart Grid.
- *Demand Response Forecasting* – Calibrate a model for controlled and voluntary demand response to various factors like weather, prices, and conservation announcements to be used in short-term load forecasting.
- *Long-Range Planning*–Show how aggregate load shapes change because of external factors like weather, prices, and incentives.
- *Energy Policy*–Determine how to represent Smart Grid benefits for end-users, aggregators, utilities, and the general public.

These insights may be achievable from the foundation provided by the OLS model. It represents fundamental appliance behaviors and may be scalable to larger systems in a way that helps answer key stakeholder questions.

BIBLIOGRAPHY

[1] M. AboGaleela, M. El-Sobki, and M. El-Marsafawy. A two level optimal DSM load shifting formulation using genetics algorithm case study: Residential loads. In *Power Engineering Society Conference and Exposition in Africa (PowerAfrica).* IEEE, July 2012.

[2] M.H. Albadi and E.F. El-Saadany. Demand response in electricity markets: An overview. *Power Engineering Society General Meeting IEEE*, 2007.

[3] Paragon Decision Technology B.V. *AIMMS Modeling Guide, 2012*.
Available at http://www.aimms.com/downloads/manuals/

[4] Hung-Po Chao, Shmuel Oren, Stephen A. Smith, and Robert Wilson. Multilevel demand subscription pricing for electric power. *Energy Economics*, 8, October 1986.

[5] Austin Energy. Austin Energy website.
Available at http://www.austinenergy.com/wps/wcm/connect/4f5bf55e- f9a5-4997-8b00-c531065bd279/ResidentialAustin.pdf?MOD=AJPERES.

[6] Van Ness Feldman. FERC approves new definition of bulk electric system, reserves determination of which facilities are ”used in local distribution”. Van Ness Feldman website, January 2013.
Available at http://www.vnf.com/1126

[7] FERC. *Assessment of Demand Response and Advanced Metering, Staff Report*, October 2013.
Available at https://www.ferc.gov/legal/staff-reports/2013/oct-demand-response.pdf

[8] IEA. *Global EV Outlook: Understanding the electric vehicle landscape to 2020*. IEA website, April 2013.
Available at http://www.iea.org/publications/freepublications/publication/GlobalEVOutlook 2013.pdf

[9] Yee Wei Law, T. Alpcan, V.C.S. Lee, A. LO, S. Marusic, and M. Palaniswami. Demand response architectures and load management algorithms for energy-efficient power grids: A survey. In *2012 Seventh International Conference on Knowledge, Information and Creativity Support Systems (KICSS),* pages 134–141, November 2012.

[10] Mike Munsell. Home energy management systems market to surpass $4 billion in the US by 2017. *GreenTech Efficiency,* September 2013.
Available at http://www.greentechmedia.com/articles/read/home-energy-management-systems- market-to-surpass-4-billion-in-the-us-by-201

[11] NERC. *2011 Demand Response Availability Report*. NERC website, March 2013.
Available at http://www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf

[12] Nest. Nest website.
Available at https://nest.com/

[13] U.S. Department of Energy. Estimating appliance and home electronic energy use. Energy.gov, November 2011.
Available at http://www.energy.gov/energysaver/articles/estimating-appliance-and-home-electronic- energy-use

[14] M. Pipattanasomporn, M. Kuzlu, and S. Rahman. An algorithm for intelligent home energy management and demand response analysis. *Smart Grid, IEEE Transactions*, 3(4):2166– 2173, December 2012.

Disclaimer

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.