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Modeling the Effect of Renewable Energy and Smart Appliances in Energy Reduction of Residential Homes Using GridLab-D

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I. Introduction and Background

When used in concert, microgrid and smart grid technologies have the ability to transform the way power is delivered. A microgrid is a localized energy grid with a colocated set of power generation sources and loads, with autonomous control, which can operate independently of the traditional power grid [1]. As a result of this ability for autonomous control, it is possible for microgrids to connect to the main power grid or act in an "islanded" mode. Microgrids can be more efficient than traditional grids due to the proximity of power generation and use [2].

The smart grid can be considered an evolution of the traditional grid, which uses technology to manage electricity demand. The benefits of smart grid technology are manifold. With smart grid technology, load balancing is possible, which allows for storage of excess electrical power for later use. [3] In addition, smart grid technology can allow for increased integration of renewable energy into the grid. Heavy generators of energy, such as users with large amounts of solar panels, can use smart grid technology to sell any excess power to the grid that cannot be stored locally. In addition, due to the technology and sensors used in smart grid systems, there is an additional ability to track and control power usage and support sustainable use of power. In addition, smart appliances and the "Internet of Things", or IoT, can integrate with smart grid technology in order to continue to change the way we use energy. Smart meters, sensors, and controls integrated into everyday objects can ensure judicious power use—for example, only activating heating in a residence when movement is detected [4].

This paper details a senior design project that quantifies the energy savings achievable by using solar power and smart thermostats in Washington DC residential homes during the summer and winter seasons. The project was conducted by a group of three students from the Departments of Electrical and Computer Engineering and Mechanical Engineering at the

University of the District of Columbia. GridLab-D, a free software simulation package developed by the Department of Energy, was used to conduct the simulations.

To simulate a residential area, a model consisting of twenty residences, including single family homes and multi-family apartments was created using XML. Each home was assigned several attributes, including the number of inhabitants, type of appliances present, size and insulation of the homes, possible solar panel installation, and the number of stories, ceiling height and the direction of windows in each home. This information was combined with U.S. National Solar Radiation Database climate data, as well as daily power use schedules, in order to create a base simulation scenario. The data produced by this simulation compares the overall load on the smart grid at various times of day. The results of the simulation show that during the winter, there is a 20% reduction in peak load for the morning peak and a 10% reduction in load for the evening peak. During the summer, there is a 33% to 50% reduction in peak loads using the smart thermostat versus the traditional thermostat. Summer reduction is far more pronounced due to the influence of solar panels on the model. In this model, energy reduction is achieved with no loss of occupant comfort. The project was conducted by our senior undergraduate students in the Spring of 2016 and was funded by the Xerox Corporation and the National Science Foundation.

The rest of this paper is structured as follows. In Section II, the load balancing model using GridLab-D is explained, the smart appliances used in the model are described, and the XML structure of the model is defined. Section III of the paper shows the results of the GridLab-D model. In Section IV, the benefits and challenges of this multi-disciplinary capstone project for out students and dynamics of the inter-departmental cooperation between our electrical and mechanical engineering students are discussed. Finally, the conclusions are provided in Section V.

II. LOAD BALANCING USING GRIDLAB-D

GridLab-D is an agent-based modeling system developed and maintained by the U.S. Department of Energy’s Pacific Northwest National Laboratory and is provided to the public free of charge. In addition, the documentation included with GridLab-D is extensive and allows users with a basic knowledge of XML and command line parameters to begin use of the system to model smart grid technology. The system uses multiple differential equations to model the power use of various elements within a smart grid system over time. With built-in modeling for residential, industrial, and commercial uses, it is possible to use GridLab-D's algorithms to create detailed models of how the smart grid evolves over time [5]. GridLab-D is also capable of handling a variety of systemic externalities that will also affect power use. These include macro-level effects on the environment such as weather data, various power demand profiles, and even individual structural variables such as the ceiling height of a building or the number of occupants in a building. GridLab-D allows for the individual creation of models to suit almost any situation using XML. This application of GridLab-D uses the residential model within the software to test the effect of smart thermostats on a particular residential, smart microgrid system.

GridLab-D is a C++ based modeling tool, and is open source. It was chosen for this application due to its use of C++ and XML. Several other tools for modeling smart grid systems also exist based on user preference. For example, OpenDSS is an open-source Delphi-based system for modeling smart grid systems and is also freely available from the Electric Power Research Institute [6]. DER-CAM, which stands for Distributed Energy Resources Customer Adoption Model, is a tool made available by Lawrence Berkeley Labs. This tool focuses on the economic cost of operating on-site generation and combined heat and power systems [7].

A. Smart Appliances

Smart appliances have the ability to connect to one another as well as the Internet. While this in itself can be useful, when combined with the smart grid, this means that the appliances have the ability to communicate with the smart grid to indicate power use levels. This will also allow for the appliance to respond to the current state of the smart grid [8]. For example, if the grid is being overly taxed at the moment due to peak power demand, the appliance will be able to put off tasks that are not as important or that are not being expressly demanded at the time.

In addition to making the home more comfortable, automation of this nature assists with load balancing. Load balancing requires that the smart grid has knowledge of all of the inputs and outputs in order to ensure that sharp peaks in power usage do not occur. The automation inherent to smart appliances can assist. There are many smart appliances that engage in learning of consumer preferences. Many of these preferences are set through the enhanced device control that smart appliances exhibit. For example, a user could set thermostat preferences through the appliance itself, or even through a device such as the user's phone. When this occurs, the thermostat records the preference for future recall, helping to foster a body of preferences for the future. Eventually, the thermostat can begin to balance user needs and preferences with overall power use. It is even possible for smart appliances to begin interacting throughout the home—for example, only setting heating or cooling in a room when a user is in that particular room [9]. While it is clear that smart appliances, and thermostats in particular, can have a profound effect on comfort, GridLab-D can be used to quantify the benefits of the smart thermostat in a particular situation.

B. Model

For this simulation, a model was constructed from a base situation—a medium-density residential block in Washington D.C.'s Petworth neighborhood consisting of twenty separate residences. Two of these are multi-family residences, consisting of six apartments each, with a square footage of 700 square feet with a variance of 50 square feet. The other 18 residences were single-family homes with a square footage of 1700 feet, with a variance of 400 feet. These values were obtained with the assistance of the U.S. Census Bureau's American Housing Survey, which can be used as a basis for determining the nature of housing in a given area [10]. With GridLab-D, these variances allow for randomization in the model with 400 feet as the value for one standard deviation. In addition, five separate power demand schedules were generated and distributed amongst the residences. These separate power demand schedules indicate when power is used by each residence, and how much power is demanded by each residence's appliances [11].

These five schedules were based off of power schedule examples written for GridLab-D andpublished with the GridLab-D package of examples included with the download of the software. Five separate schedules were written in order to simulate different types of users. As the general mode of power transmission in Petworth is underground wires, a network of underground wires and transformers were also included in the model. A few houses have also begun to reap the benefits of solar panels, which have also been taken into account with the GridLab-D model. Two of the single-family homes have been fitted with solar panels, keeping with the residential adoption trend in the year 2016 [12]. GridLab-D supports the use of climate data in TMY2 (typical meteorological year) format. This format allows for an entire year of meteorological information to be transmitted in to GridLab-D, which can simulate any weather throughout the year. For simplicity's sake in this model, a standard day in January and another standard day in August were chosen. This allowed for comparison between summer and winter loads in each situation. One model simulated the use of smart thermostats, while the other model acted as a control. An example of the XML code used in the model follows:

```
object house {
 name house1;
 floor_area 1732;
 heating_system_type GAS;
 cooling_system_type ELECTRIC;

object lights {
 type INCANDESCENT;
 placement INDOOR;
 installed_power 1 kW;
 power_factor 0.95;
 demand my_schedule;
 };
}
```

III. Simulation Results and Discussion

The results of the simulation show that there is a definite reduction in peak load when using the smart thermostat, and that this effect is far more pronounced during the summer months. As shown in Figure 1, during the winter, there is a 20% reduction in load for the morning peak, and a 10% reduction in load for the evening peak. Much of this reduction in peak use is due to more appropriate use of heating and cooling cycles, as well as the ability to use stored energy. For the Summer months, as shown in Figure 2, the reduction in the load for the morning peak and for the evening peak are 33% to 50%, respectively, in exchange for a slightly higher power use throughout the day. This effort at load balancing also assists with the adoption of renewable energy—if peak energy use is lower, it's more likely that the microgrid could support itself and supply its own power from renewables such as solar. The effect is also probably more pronounced in the summer as solar energy becomes more viable and easily used.

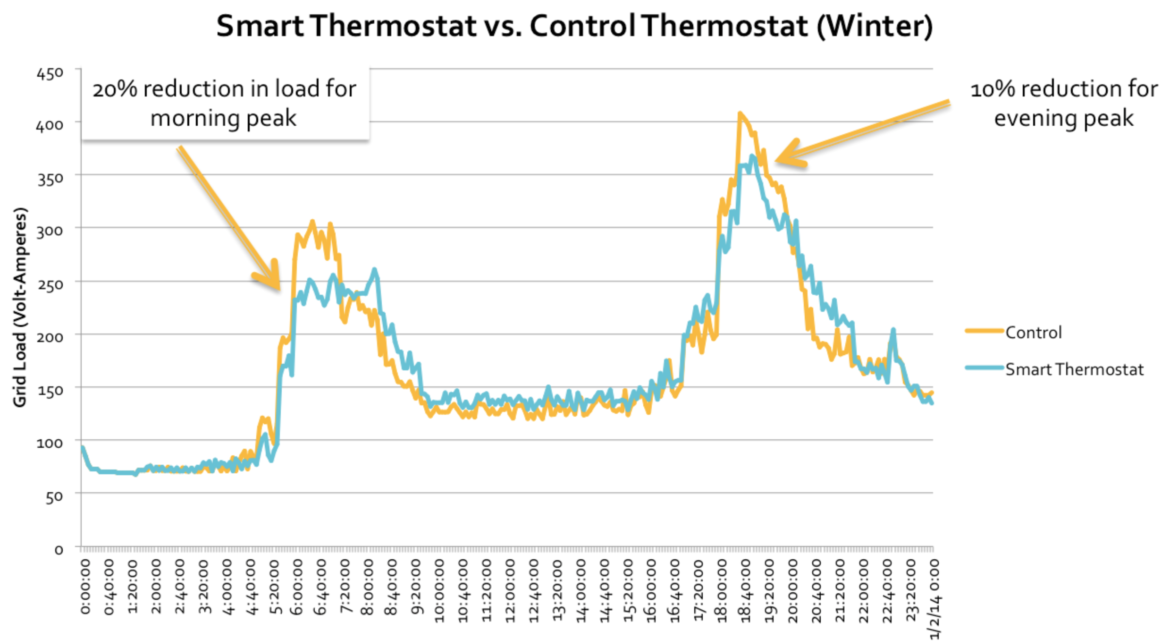

Figure 1: Smart Thermostat vs. Control Thermostat Winter Data

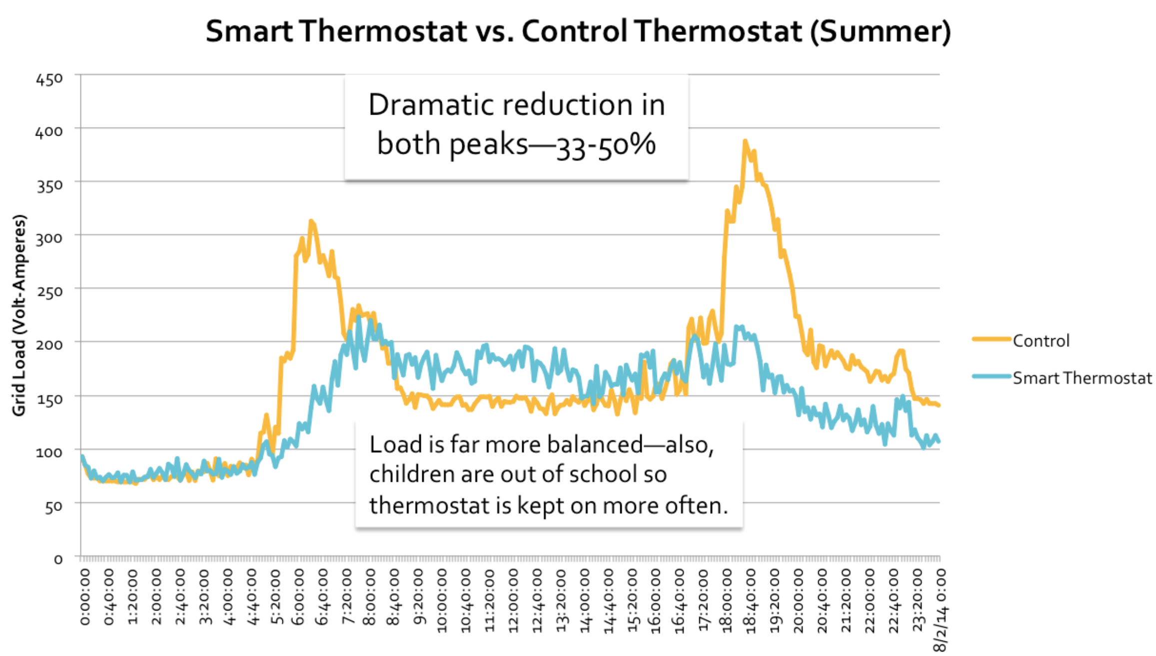

Figure 2: Smart Thermostat vs. Control Thermostat Summer Data

This exercise shows that it is possible to preliminarily use GridLab-D in order to model a smart grid and show the benefits of its adoption. We note that our results obtained here are comparable with other studies (i.e., [13]-[14]), which individually look at the use of smart appliances and microgrids with solar capabilities. For example, in [13], a 25.4% reduction in energy use is reported when smart thermostats and appliances are used in residential homes. In [14], using microgrid and smart grid technology for the reduction of peak loads, it is shown that an annual resuction of 32% in energy use could be achieved, where community power flow control strategies and consumption of self-generated renewable energy is utilized.

GridLab-D has many benefits; it is an extremely flexible system, which allows for the creation of various power load profiles. In addition, GridLab-D comes with a variety of hard-coded functions for residential, commercial, and industrial power use modeling. However, there are a few shortcomings to GridLab-D such as the lack of a graphical user interface and visualizations needing to be created through the use of auxiliary tools. Despite these shortcomings, GridLab-D is an exceptionally powerful piece of software, and understanding its capabilities will assist in the creation of smart grid model.

The next step in this project could include convincing local jurisdictions to encourage the installation of solar panels, smart thermostats, and microgrid technology on a small scale to test the findings created by this model. The District of Columbia Department of Energy and Environment currently sponsors a variety of programs, including the Affordable Solar Program and Solar for All that could assist with the adoption of solar panels in neighborhoods throughout Washington. [15]. In addition, there have already been a few studies completed laying out the preliminary work necessary in order to start installation of microgrid technology. These steps included evaluating microgrid potential and potential microgrid sites, developing a financial model for financing and installation of the microgrids, and framing the possible regulatory barriers towards microgrid installation [16]. The use of this model and GridLab-D, combined with American Housing Survey data could be a step forward in determining what sites within the District of Columbia are ideally suited for microgrid installationss.

IV. Cross-Department Collaboration

Cooperation between students in the Electrical and Computer Engineering and the Mechanical Engineering Departments for this project has proved fruitful and an extremely positive experience. A capstone project with a group of students with different backgrounds allowed students to utilize their varying skill sets. While there are many core courses in the engineering curriculum that are included in both the electrical and mechanical tracks, the divergence of courses and emphases between departments meant that the students needed to learn each other's strengths to determine who would be best at various aspects of the project.

Electrical and computer engineering students were able to help compose the basis of the model and determine the initial direction of the project. In addition, mechanical engineering experience helped to take this project's concept into completion. Utilizing the mechanical engineering student's experience with modeling and operations research, the group was able to modify the GridLab-D to model the experiment.

As the nation's only urban land-grant university, the University of the District of Columbia has a special focus on urban sustainability, which is reflected in its curriculum and research focuses. The experience that these students brought to the framing of this project was integral to its success.

Collaboration through the capstone project allowed students to share the lessons they've learned through their internships or research projects in a concrete manner. One student, who had done extensive work with XML and Python in a previous internship, was able to share his experience and knowledge with the other students in coding the residential model. Another student was able to share her experience with the data visualization tool Tableau in order to explore the results the model generated. Both of these experiences would not normally have emerged in the classroom, and students would not necessarily have had other opportunities to share these practical work skills with one another. As a result, this multi-disciplinary capstone project gave students another arena to refine the skills they learned in various workplaces and share them with one another.

A challenge our students faced in conducting this project was course scheduling. Students in their third and fourth years in an engineering curriculum, particularly at a small institution, are often scheduled together with their cohort. All mechanical engineering students often take the same classes, and conversely, all electrical engineering students often take the same classes. When allowing for work, research projects, and extracurricular activities, these classes may not be scheduled in a way that allows students to easily work together on their capstone projects. If multi-disciplinary collaboration is desired, departments must be flexible and communicate with one another to ensure that classes are scheduled accordingly.

V. CONCLUSIONS

This paper presented the results of a Xerox Project conducted by three undergraduate engineering students from the Departments of Electrical and Computer Engineering and Mechanical Engineering at the University of the District of Columbia. GridLab-D, a simulation software developed by the Department of Energy, was used to conduct the simulations and the benefits of using smart thermostats as well as renewable energy resources in reducing peak energy consumption was quantified by simulating a residential area..

Looking towards the future of energy infrastructure in the Washington D.C. area, microgrid and smart grid technology are two very promising emerging technologies that will help shape the way the District of Columbia receives energy. The confluence between smart appliances and load scheduling with smart grid technology are an integral component in attempting to reduce the amount of stress on the grid, and GridLab-D is an excellent way of modeling this.

Finally, students were able to successfully work across disciplines to prove the effectiveness of GridLab-D and show the benefits of a multi-disciplinary capstone project. Students were able to share their experiences from the classroom and the real world, and come together to create a project that has the potential to benefit the District of Columbia residents.

VI. Acknowledgement

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