A simulation platform to demonstrate active demand-side management by incorporating heuristic optimization for home energy management

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A Thesis

entitled

A Simulation Platform to Demonstrate Active Demand-Side Management by Incorporating Heuristic Optimization for Home Energy Management

by

Nikhil Gudi

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science Degree in Electrical Engineering

Dr. Lingfeng Wang, Advisor

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The University of Toledo

August 2010
An Abstract of

A Simulation Platform to Demonstrate Active Demand-Side Management by Incorporating Heuristic Optimization for Home Energy Management

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The University of Toledo
August 2010

Demand-Side Management (DSM) can be defined as the implementation of policies and measures to control, regulate, and reduce energy consumption. This document introduces home energy management through dynamic distributed resource management and optimized operation of household appliances in a DSM based simulation platform. The principal purpose of the simulation platform is to illustrate customer-driven DSM operation, and evaluate an estimate for home electricity consumption while minimizing the customer’s cost.

A heuristic optimization algorithm i.e. Binary Particle Swarm Optimization (BPSO) is used for the optimization of DSM operation in the platform. The platform also simulates the operation of household appliances as a Hybrid Renewable Energy System (HRES). The resource management technique is implemented using an optimization algorithm, i.e. Particle Swarm Optimization (PSO), which determines the distribution of energy obtained from various sources depending on the load. The validity of the platform is illustrated through an example case study for various household scenarios.
For my parents, fiancé, and friends
Acknowledgements

I sincerely thank my advisor Dr. Lingfeng Wang and co-advisor Dr. Vijay Devabhaktuni for giving me the opportunity to pursue my research under their guidance. It has been a great learning experience working with them. I would also like to express my deepest gratitude towards them for offering instructive advice at all times, treating me with endurance, and constantly pushing me to do better every time.

Last, but not the least, I thank my family, fiancé, and friends who have been a constant source of encouragement and support for me throughout my journey in the Masters Degree program.
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<th>Description</th>
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<tbody>
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<td>AMI</td>
<td>Advanced Metering Infrastructure</td>
</tr>
<tr>
<td>BPL</td>
<td>Broadband over Power Line</td>
</tr>
<tr>
<td>BPSO</td>
<td>Binary Particle Swarm Optimization</td>
</tr>
<tr>
<td>CBP</td>
<td>Central Board of Power</td>
</tr>
<tr>
<td>CPP</td>
<td>Critical Peak Pricing</td>
</tr>
<tr>
<td>DR</td>
<td>Demand Response</td>
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<tr>
<td>DSM</td>
<td>Demand-Side Management</td>
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<tr>
<td>EE</td>
<td>Energy Efficiency</td>
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<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>HAN</td>
<td>Home Area Network</td>
</tr>
<tr>
<td>HRES</td>
<td>Hybrid Renewable Energy Systems</td>
</tr>
<tr>
<td>ISO</td>
<td>Independent System Operator</td>
</tr>
<tr>
<td>MDMS</td>
<td>Meter Data Management System</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-in Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>PLC</td>
<td>Power Line Communication</td>
</tr>
<tr>
<td>PSO</td>
<td>Particle Swarm Optimization</td>
</tr>
<tr>
<td>PTR</td>
<td>Peak Time Rebate</td>
</tr>
<tr>
<td>PV</td>
<td>Photo Voltaic</td>
</tr>
<tr>
<td>RF</td>
<td>Fixed Radio Frequency</td>
</tr>
<tr>
<td>RTP</td>
<td>Real Time Pricing</td>
</tr>
<tr>
<td>SOC</td>
<td>State-of-Charge</td>
</tr>
<tr>
<td>SQL</td>
<td>Structured Query Language</td>
</tr>
<tr>
<td>TOU</td>
<td>Time-of-Use</td>
</tr>
<tr>
<td>WAN</td>
<td>Wide Area Network</td>
</tr>
<tr>
<td>WTG</td>
<td>Wind Turbine Generator</td>
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Chapter 1

Introduction

1.1 Background

The present day utility grids in the United States and other nations are source-defined centralized power distribution systems. The major issue with the present day grids is the outdated design of the infrastructure, owing to which, the infrastructure cannot easily be expanded to meet the ever increasing power demands of the 21st century. In the next decade, power demand is expected to rise by nineteen percent and the current infrastructure has the capability to increase its productivity by only six percent. The increase in production of electricity in the past few decades without major changes to the infrastructure has made the grid system highly unreliable. Blackouts and grid failures have been common problems to be addressed, having resulted in as much as billions of dollars in losses. A solution envisioned by academia and industry is the “smart grid”. Smart grid has a potential to enhance grid modernization thus making it more capable of addressing future requirements [1]. Smart grid defines a more distributed, communication driven, and consumer-involved power system. Such systems promise to change the scenario of the energy distribution model and redefine the relationships of all the entities involved with energy consumption and distribution. Despite the allocation of billions of dollars for the development of new smart grid
technologies, it is imperative that economic benefits for residential customers are justified [2].

Both communication and consumer participation are extremely important components of smart grid systems. In the last decade, the internet has emerged as an efficient and reliable communication medium for transferring large quantities of information [3]. Lately, the internet is being utilized for electric power-oriented communication. Currently, Advanced Metering Infrastructure (AMI), Meter Data Management System (MDMS), Home Area Network (HAN), and Demand-Side Management (DSM) are being provided as options for a smart grid [3].

AMI measures, collects, and analyzes energy usage of a household from data measured through advanced devices (e.g., state-of-the-art electricity meters for collecting real-time data), which communicate through various mediums including Broadband over Power Line (BPL), Power Line Communication (PLC), Fixed Radio Frequency (RF), etc. Specifically, the meter data is received by the AMI host system and sent to the MDMS that manages data storage and analysis to provide the information in a useful form to the utility. Figure 1.1 shows the building blocks of AMI [4].

![Figure 1.1: Building blocks in a typical AMI.](image-url)
Advances in AMI technology and integration with HAN have resulted in the development of DSM techniques as shown in Figure 1.2 [5].

The development of smart grid has resulted in an increased interest in DSM programs [6]. DSM can be defined as the implementation of policies and measures to control, regulate, and reduce energy consumption [7]. Typically, DSM determines the various activities undertaken by an electric utility and the consumers and uses such activity-related data to regulate the quantity and time of energy consumption. Such an approach is critical to effectively manage the overall electricity demand across North America [8]. A typical household electricity consumption distribution/pattern is shown in Figure 1.3 [9]. As seen in Figure 1.3, there exists time period(s) during the day characterizing peak demand of electricity [10]. DSM manipulates the residential electricity usage to reduce cost by altering the system load shape [11]. The common techniques used for load shaping are peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape [12].

![Figure 1.2: Development of various technologies contributing to DSM.](image-url)
DSM can be classified into (i) Energy Efficiency (EE) programs and (ii) Demand Response (DR) programs. EE programs are designed to reduce electricity consumption throughout the year by focusing on reduction of energy consumption and overall demand for energy. DR programs are automatic with a processing unit having the right to moderate or turn-off certain appliances (e.g. air-conditioners, pool pumps, washing machines, etc.) for a short period of time at customer sites [10]. In a DR program, data is transmitted from the utility to a HAN, through a smart meter.

DSM techniques such as demand dispatch provide round-the-clock deployment and assessment, thereby providing a qualitative approach to balancing energy generation and load for the electric grid [13]. DSM plays a vital role in facilitating greater connection of intermittent renewable generation [14]. The future of the overall energy scenario will
constitute the increased utilization of small distributed energy resources for generating electricity [15].

One of the important applications of smart grid is that it encourages home and business owners to invest in microgeneration technologies in order to supply some of their own energy and reduce the demand on the electric grid. Among the various renewable energy resources, the most popular sources are the solar and wind energy. These energies are non-exhaustive, site-dependent, and green. Microgeneration models consist of various sources of energy such as wind turbines, Photo Voltaic (PV) panels, fuel cells, etc. [16]. The combination of these energy sources in different patterns result in multiple designs of Hybrid Renewable Energy Systems (HRES) [17]. A generic architecture of HRES is as shown in Figure 1.4.

HRES technology can be generalized as a system that utilizes energy from both conventional and renewable sources. In comparison to conventional power systems, HRES reduces fuel consumption and emissions thereby making the system cost-effective, green, and highly reliable in terms of producing power. Proper load and energy management is important for better efficiency and endurance of HRES [18].

![Figure 1.4: Architecture of HRES.](image-url)
The intermittency of renewable energy sources results in unpredictable fluctuations that may appear in the power output [19]. The energy obtained from renewable sources is not subject to the demand, which results in an imbalance in the system. These problems can be resolved by including intermediate storage mechanisms such as batteries, water pumping, compressed air, fly wheels, ultra-capacitors, etc. [20].

HRES invariably includes battery storage to meet the demand during either peak demand or non-availability of energy from renewable sources. The effectiveness of a battery storage system is present during peak demand or non-availability of energy from renewable sources, and is dependent on the amount of energy stored in the battery. The presence of multiple energy sources results in the requirement of a resource management system that supervises the energy resources [17].

The energy obtained from various renewable sources can be either utilized for powering the load or for recharging the battery. This results in the requirement of an optimization algorithm that creates a balance between the consumption of energy from the renewable sources and the recharging of the battery source.

The smart grid is still in the development phase and much research involves paper designs, and laboratorial experiments. The developments of these techniques have to be implemented by rigorous simulations of real-time environments [21]. Several energy management software such as Energy Lens – Energy Management Software and Greendash Home Energy Management Software have been developed in the recent past [22, 23]. These smart applications act as energy monitoring hubs that obtain real-time data from various household energy devices and communicate the data to the end-user. The software packages provide frequent energy information and control options to the end-user. The software platforms run intelligent algorithms for providing optimal, profitable solutions to the end
user. Presently, the various energy management software packages do not feature the real-time operation of DSM.

1.2 Research Approach

This document presents the design and development of a DSM based real-time simulation platform, demonstrating home energy management. This platform utilizes a Binary Particle Swarm Optimization (BPSO) algorithm for determining the operation of appliances and real Particle Swarm Optimization (PSO) for energy resource management in a given household. The platform exhibits bidirectional data communication in a smart grid. The platform can be used for simulations that help determine the financial benefits of a smart grid facilitated by active DSM. The platform is suitable for educational purposes in terms of understanding the what-if and how of DSM. For instance, this platform has been demonstrated for introducing DSM in a graduate course entitled “Renewable Energy and Smart Grid” in the Department of Electrical Engineering and Computer Science at The University of Toledo, and was well received by the students.

1.3 Organization

The remainder of the document is organized as follows: Chapter 2 discusses the various features of smart grid and DSM. Chapter 3 provides an overview of the simulation platform. Chapter 4 discusses the various renewable energy resource modeling techniques. Chapter 5 describes the concept of home energy management through particle swarm optimization approach. Energy consumption and cost analysis are presented and discussed in Chapter 6. Finally, the document wraps up with some conclusions and future research suggestions.
Chapter 2

Smart Grid and Demand-Side Management

2.1 Smart Grid

The worldwide rise in energy demand accompanied by the rise in prices of petroleum products has led to a profound change in the present day energy infrastructure. The United States’ century-old electric power infrastructure is running near capacity. There is increasing consent among federal and state policymakers, business leaders, and other key electric grid stakeholders to develop a technologically enhanced electric grid, or “smart grid” [1]. The smart grid can be defined as an intelligent grid having the capacity to be extremely efficient and deliver energy at an affordable cost in the decade of high inflation [24].

The last few decades have witnessed an exponential increase in power demand which has resulted in a drastic drop of the grid reliability. Previously, grid reliability was mainly ensured by having excess capacity in the system, with unidirectional electricity flow to consumers from centralized power distribution systems. With the internet becoming a highly efficient and reliable source of communication in the past few years, it has become a source of communication of important and large data (e.g. electric power communication) [5].

Both industry and academia have identified the following aspects that need to be
considered when designing a future electric grid [24]:

- Electric power causes approximately 25 percent of global greenhouse gas emissions and utilities are evaluating the need for a more green electric system.
- Renewable and distributed power generation will play a more prominent role in reducing greenhouse gas emissions.
- DSM promises to improve energy efficiency and reduce overall electricity consumption.
- Real-time monitoring of grid performance (*e.g.*, agents deployed along the electric line) will help identify the concerns over grid reliability thereby increasing grid reliability and utilization, reducing blackouts, and increasing financial returns on investments in the grid.

These changes on both the demand and supply side require a new and more intelligent system that can manage the increasingly complex electric grid [24]. A smart grid provides a foundation for making this transformation of integrating various technologies, ideas, concepts, and primarily the internet [1].

Technology enables the electric system to become “smart.” Near-real-time information allows utilities to manage the entire electricity system as an integrated framework, actively sensing and responding to changes in power demand, supply, costs, quality, and emissions across various locations and devices [25].

A completely enhanced smart grid can be summarized to provide these features [3]:

- Extremely high reliability.
- Cost effective.
- Integrate conventional and renewable sources of energy.
- Be environmentally friendly.
- Providing easy integration for future research and technical enhancements.

Possible smart grid architecture is as shown in Figure 2.1 [26].

The United States’ Department of Energy has defined the following as important aspects of the smart grid [1]:

- **Intelligent** – having the capacity to identify system overloads and re-route power to prevent or minimize a potential outage; ability to make autonomous decisions when there is a requirement of resolution faster than the time taken for humans to respond, keeping the overall goals of utilities, consumers and regulators intact.

Figure 2.1: Possible architecture of smart grid.
- **Efficient** – capable of meeting increased consumer demand without considerable change to the infrastructure.

- **Accommodating** – capacity to accept energy from any source (*e.g.* solar, wind, coal, natural gas, etc.); having the capacity to integrate future ideas and developments in the field of technology.

- **Motivating** – enabling real-time communication between the consumer and utility so consumers can tailor their energy consumption based on individual preferences, such as price and/or environmental concerns.

- ** Opportunistic** – providing new opportunities and markets for capitalizing on plug-and-play kind of technology.

- **Quality-focused** – capacity to reduce sags, spikes, disturbances, and interruptions and provide clean quality power.

- **Resilient** – capacity to resist physical and technological attacks and natural disasters as it becomes more decentralized and reinforced with smart grid security protocols.

- **“Green”** – has no/less residue which can result in direct/indirect increase in pollution and climate change.

### 2.2 Renewable Sources of Energy

To meet the future energy requirements of an expanding global economy, new techniques for finding energy sources will be required. The world is moving towards utilizing renewable energy sources in a large scale manner to meet the global demand. Considering various concerns regarding climate change, the need for distributed solar and wind power is critical. There has been a gradual increase in research for harnessing energy and developing
cost-efficient renewable sources of energy, but many complex and ill-faced problems still exist [27].

Renewable energy technologies offer important benefits over conventional energy sources. Renewable resources are abundant and more widely available in comparison to fossil fuels. Different types of renewable resources are available depending on geography. Various renewable energy sources can complement each other; taken together they can contribute appreciably to energy security and regional development in every nation of the world. This increases national independence for energy thus reducing the political instabilities and other such concerns [28].

One important benefit of renewable sources is their modular nature. This permits flexibility in load matching. Current markets for renewable energy technologies range from microgeneration (micro grid) to centralized energy production (distribution grid). For centralized energy production, renewable energy systems are relatively high-cost compared to conventional technologies such as natural gas combined-cycle power plants. However, after the initial investments have been made, the economics of renewable energy technologies improve in comparison to conventional technologies because operating and maintenance costs are low compared with those incurred using conventional fuels. This is pertinent in regions of the world where fuel prices are relatively high, and will be especially true in the future as fuel prices increase [28].

The fuel required for both solar and wind energy is natural, hence their cost is not only constant but zero for the life of the system. Renewable energy systems generate little to no waste or pollutants that contribute to acid rain, urban smog, and health problems and do not require environmental cleanup costs or waste disposal fees. Renewable energy systems do not have any waste byproducts that contribute to world pollution; hence their
implementation could have a drastic effect on the world climate [28].

2.3 Demand-Side Management

DSM works to reduce electricity consumption in homes, offices, and factories by continually monitoring and actively managing how appliances consume energy. It consists of DR programs, smart meters, dynamic electricity pricing, smart buildings with smart appliances, and energy dashboards. DSM manipulates residential electricity usage to reduce cost by altering the system load shape [9].

Common techniques used for load shaping are peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape as shown in Figure 2.3 [12].

![Diagram of load-shape objectives](image-url)

Figure 2.2: Load-shape objectives [12].
- **Peak clipping** – reduction of grid load mainly during peak demand periods.

- **Valley filling** – improvement of system load factors by increasing load during off-peak periods.

- **Load shifting** – reduction of grid load during peak demand and simultaneously building load across off-peak periods.

- **Conservation** – reducing the load throughout the day by utilizing more energy efficient appliances or by reducing overall consumption.

- **Load building** – increasing the load throughout the day by increasing the overall consumption.

- **Flexible load shape** – specific contracts and tariffs with the possibility of flexibly controlling consumers’ equipment.

DSM can be classified into [10]:

(i) **EE programs** – designed to reduce electricity consumption throughout the year by focusing on reducing energy consumption and overall energy demand.

(ii) **DR programs** – automatic with a processing unit having the right to moderate or turn-off certain appliances (e.g. air-conditioners, pool pumps, washing machines, etc.) for a short period of time at customer sites.

The implementation of DSM programs has the following effects [29]:

- Improved energy system efficiency through improved generation efficiency and system load factor.

- Reduced construction costs for new energy facilities by reducing the peak demand.

- Reduced CO$_2$ emissions through efficient generation and minimizing thermal generation.
• Decreased consumer electricity bills through the use of energy efficient appliances and also monitoring the time of consumption of electricity.

• Reduced power cuts/shortages and increased system reliability.

Common issues associated with integrating DSM as a component of smart grid:

• If the cost of developing a smart home is significant and cost savings is minimal, then a user does not feel the need for making the shift. Smart homes should be made affordable for every citizen. To accomplish this, various technologies associated with smart homes have to be made inexpensive if widespread implementation is to be achieved.

• The concept of DSM involves the integration of various appliances with a smart control unit capable of bidirectional communication with the utility. One problem that arises with these features is various compatibility issues between the different appliances, various smart controllers, and communication protocols. The various devices available off-the-shelf for consumers should be interoperable, the communication mediums should meet pre-defined standards, and smart controllers should have universal compatibility.

• DSM involves transmitting large amounts of data between the consumer and the utility. Consumer privacy becomes a very important aspect of DSM design. Important data from the consumer stored in MDMS should not be utilized for false marketing and advertising.

• The data transmitted across the various communication mediums requires high-level security to deter identity theft and other personal security related issues.
The design of various cost-rate plans have to be made such that they address the requirement of all consumer classes. Different cost-rate plans have to be identified for different end-users (e.g. residential, commercial, etc).

2.4 **Demand Response**

DR refers to a wide range of actions which can be taken at the customer side of the electricity meter in response to particular conditions within the electricity system (such as peak period network congestion or high prices) [14]. DR programs have been aimed both at industrial and residential users. Industries have been provided the option of obtaining low energy rates in lieu of reducing power consumption during grid demands. Residential users have been targeted through Direct-Load-Control programs which control appliances such as air conditioning, pool pumps, etc.

DR programs can be classified as [29]:

- Economic or price response programs.
- Emergency or reliability programs.
- Ancillary service programs.
- Peaking alternative.

During periods of peak energy usage, utility companies send electronic messages that alert consumers to reduce their energy consumption by turning off/down non-essential appliances. In the future, alert signals will be sent automatically to appliances, eliminating the need for manual intervention [29].

If enough consumers comply with this approach, utility companies will not need to dispatch an additional power plant, the most expensive asset they operate. To increase the
number of consumers who comply, utility companies may offer cash payments or reduced billing. In principle, DR initiatives can bring about significant reductions in electricity prices as shifts of demand during peaks could reduce the need for higher marginal cost generation, offer lower cost system balancing, and decrease grid reinforcement investment. DR initiatives can also play a valuable role in achieving ambitious environmental policy objectives through facilitating increased connection of intermittent renewable generation [29].

2.4.1 The Three Levels of Demand Response

To realize large scale benefits, DR must be developed and coordinated while keeping in the mind the three levels of DR [30]:

- The first level is the response of an individual smart appliance (e.g. water heater, refrigerator, clothes dryer, or dishwasher) to a smart grid control or pricing signal.

- The second level of DR involves understanding the household communication between various smart appliances and/or other smart DR devices (e.g. solar panels, electric vehicle supply equipment, and so on). This is the role of the HAN. It is an acceptable action for the user to alter the operation of certain appliances like a water heater or an air conditioner based on the user requirement and user comfort. However, it may not be acceptable to also adjust the operation of washing machine, dryer, or dishwasher.

- The third level of smart grid DR involves evaluating the larger network comprised of hundreds to millions of homes. This may involve the monitoring of various smart appliances throughout each household via the internet and evaluating dynamic-pricing/grid loading.
2.5 Dynamic Pricing

Amongst the various techniques and strategies developed for managing the peak demand, user-defined pattern modification of electricity usage is the most popular technique utilized [31]. The development of customer cost-rate plans can be subdivided into, i) Developing the Critical Peak Pricing with Time-Of-Use (TOU) Rate, ii) TOU Rate, iii) Peak-Time Rebate (PTR), and iv) Real Time Pricing (RTP) [32]. A smart grid communication network permits automatic meter reading at scheduled intervals during which the utilities can provide time- and demand-based pricing including:

- **TOU** – specific time intervals correspond to different pricing tiers (i.e. off-peak and peak) [33].
- **CPP** – a process of identifying spikes in peak demand and communicating price changes with end users to provoke shifts in energy consumption [34].
- **PTR** – customers are provided with rebates for reducing their electricity consumption during peak periods or during high price time periods [34].
- **RTP** – the ability to not only change energy prices based on fluctuations in the cost of generation but also to notify consumers (and consumer devices) to integrate demand-side applications to participate in load-shifting decisions [35].

Dynamic retail pricing, especially RTP, has been identified as one of main tenets for providing DR in electricity markets. Dynamic pricing includes calculating the total load for a given area while determining the cost of electricity in real-time. As the load increases, the cost of consumption of electricity increases. Hourly electricity pricing is one mechanism for stimulating price responsive demand. Presently, utilities are providing standard or default service to evaluate the effect of RTP, often at a capped or administratively determined rate [36]. DR programs, which offer explicit payments to customers for load reductions represent
a different and potentially complementary type of approach. The direct effect of RTP is a function of the amount of load remaining on the rate and the price responsiveness of the customers [37].

2.6 Smart Buildings with Smart Appliances

Buildings are becoming smarter in that their ability to reduce energy usage is increasing. Traditional stand-alone, complex systems that manage various appliances (e.g. heating, ventilation, air-conditioning, and lighting) are now converging towards a common Information Technology infrastructure that allows these devices to communicate with each other and coordinate their actions which can reduce waste [25].

2.7 Energy Dashboards

Consumers will reduce their energy usage and greenhouse gas emissions if they can see their energy footprint. Online energy dashboards provide real-time visibility into consumer energy consumption while offering suggestions on the methods to minimize consumption. Recent university studies have found that simple dashboards can encourage occupants to reduce energy usage in buildings by up to 30 percent [25].
Chapter 3

Overview of the Simulation Platform Interface

The proposed real-time simulation platform has been designed based on the Load Management DSM program and TOU. Load management programs may either reduce electricity peak demand or shift demand from peak to off-peak periods [5]. For TOU pricing, specific time intervals correspond to different pricing tiers [33].

The platform demonstrates the operation of a smart home which is building automation control of electrical appliances (e.g. air conditioner, dishwasher, washing machine, etc.). The smart home consists of dynamic control of an intelligent interconnected network of household electronic devices. The simulated network is similar to the existing household network which comprises of a HAN connected to a Wide Area Network (WAN) which is in turn connected to the communication backbone like the “internet”. Each HAN has a set of user-defined or predefined appliances connected to a central processing unit/metering device. The platform simulates the functioning of the central processing unit through the “control-of-appliances” based operation of the algorithm. Communication between various modules is presented in Figure 3.1.
The architecture of the simulation platform is shown in Figure 3.2. The simulation platform has been developed using Java and Structured Query Language (SQL) database and is deployed online using Java Web Start. A user can login to the platform through an online website and remotely access the platform.
As shown in Figure 3.3, the Graphical User Interface (GUI) provides the user with the option to select various appliances and their properties. The appliance properties include its name, customer preference (or priority), power consumption, and the duration of its operation. The properties of each appliance are stored and retrieved from a database during the operation of the platform.

The simulation platform is divided into three main modules:

- Graphical User Interface (GUI)
- Database
- Algorithm for DSM implementation

![Figure 3.3: A screenshot of GUI in the developed simulation platform.](image)
3.1 Graphical User Interface

The GUI is sub-divided into (i) A Cost-Rate/Program Selector Window, (ii) Renewable Sources Window, (iii) The Main User-Interface Window, and (iv) A User-Defined/Pre-Defined Appliance Property Window.

3.1.1 Cost-rate/Program Selector Window

The screenshot of the cost-rate/program selector window is shown in Figure 3.4. As seen, the users are allowed to select the cost-rate program for the operation of the platform.

The cost-rate program options provided include those offered by the Central Board of Power (CBP), Independent System Operator (ISO), and the cost-rate program already subscribed by a given household. These pre-defined cost-rate plans are stored in the database and cannot be edited by the user. The window also provides a “user override” option, which allows the users to custom-define their own cost-rate plan.

![Select Program Window](image)

Figure 3.4: Screenshot of cost-rate/program selector window.
3.1.2 Renewable Sources Window

Along with the cost-rate plan selection, the user selects the different types of renewable energy sources and storage devices as shown in Figure 3.5. As seen, the users are provided with various options to select different types of renewable sources for the operation of the platform. The renewable sources option provided include the standard solar panel, wind turbine, and energy storage devices. The window also provides user-defined selection of various renewable sources.

![Screenshot of renewable sources window.](image)

Figure 3.5: Screenshot of renewable sources window.
Once the user determines the various renewable sources of energy, the platform returns to the cost-rate/program selector window (Figure 3.4). The user is provided with an option to select the cost cut-off for renewable sources of energy. This cut-off determines in real-time, the minimum cost-rate required for the utilization of renewable sources of energy (e.g. Figure 3.4 shows the renewable energy cost-rate cut-off as 0.2 cents/Kwh).

### 3.1.3 Main User-Interface Window

The screenshot of the main user-interface window is shown in Figure 3.3. The majority of the operations of the platform are performed through this window, which is divided into three parts namely “Index”, “Appliances” and “Results”.

The control buttons of the platform (e.g. Reset, Add an Appliance, etc.) are provided in the “Index” section. The “Reset” button resets the platform and removes all the appliances. Once the “Reset” button is selected, a pop-up window for confirming the reset of the platform is obtained.

The “Add an Appliance” button adds an appliance by opening the “Enter Appliance Property” window. Once the user clicks “Start”, the platform calculates both power and cost consumption and displays to the user accordingly. The user clicks “Stop” to halt the platform.

The “Appliances” section displays all the appliances that have been added to the system. The platform displays each appliance with its name, a pictorial representation of the appliance, and the appliance operational status indicator. The operational status of the appliance is represented using color-codes as indicators. When the appliance is switched off, the color of the indicator is red.
The “Results” section provides the various results/details of the simulation, such as the name of the selected cost-rate plan, the current date and time, the current hour versus cost-rate for the particular time-period, the total operational time of the platform, the total energy consumed by all the appliances, and the corresponding total cost. It also provides the status of various renewable sources and the recharging/usage status of the energy storage device.

3.1.4 User-Defined/Pre-Defined Appliance Property

The screenshot of the appliance property window is shown in Figure 3.6. This window pops-up when users click the “Add an Appliance” button in the “Index” section of the main user-interface window. This window is used to enter the various properties of the appliance including name, customer preference (priority), the power-ratings for all the duty cycles, and duration of operational-time. Standard appliances used at homes and their features are provided as drop-down boxes.

Figure 3.6: Screenshot of appliance property window.
The various options provided for further classifying the appliance are: “Manual Selection”, “User Override”, and “Multiple Duty Cycle”. A user-defined appliance can be provided using the “Manual Selection” option. Appliances such as the television and the CD player (that typically operate at user-preferred timings) are treated differently using the “User Override” option. For such appliances, name and power consumption are the only properties required, and their status can be changed at real-time. The option of “Multiple Duty Cycle” can be selected for certain appliances such as the air-conditioner and washing machine that have multiple duty cycles. Each appliance can be provided with up to three operational characteristics, with corresponding power consumption. For notifying duty cycle one, duty cycle two and duty cycle three, the color of the appliance indicator is displayed as yellow, green and magenta respectively.

3.2 Database

SQL is used as a database at the server side. The database stores appliance properties such as name, priority, power consumption, duration of operation, type of duty cycle, operational state of appliance, and start time. The SQL tables are updated at real-time.

3.3 Algorithm for DSM Operation

The user selects the type of appliance selection (priority based or BPSO based) technique for implementation of the platform. In priority based appliance selection, the platform evaluates the operability of an appliance based on the order of the priority of all the appliances and their duration of operation. Real-time cost-rates are obtained from the database. Along with the cost-rate plan selection, the user selects the different types of renewable energy sources and storage devices. Once the simulation platform is started,
various parameters (e.g. total energy consumed, total cost, time elapsed and operational status of the appliances) are calculated and updated in real-time. In BPSO based appliance selection [38], the platform evaluates the set of appliances that have to be operational at a given time of the day based on a set of defined rules and the cost-rate at the particular time of evaluation.

The functioning of the platform is depicted in the form of a flow-chart shown in Figure 3.7. Once the platform is launched, it verifies if a cost-rate program is already selected by the user. If it is not, the platform alerts the user through a pop-up window and facilitates selection of a program. The next step for the user is to select and configure all the household appliances. Upon finalizing such selection:

- The user-selected-algorithm (priority based or BPSO based) evaluates the set of appliances that have to be operational at a given time of the day based on a set of defined rules and the cost rate at that particular time;

- The platform calculates the total energy consumption of all the appliances operational at that time;

- The platform retrieves real-time solar insolation (radiation) data and wind speed data from the database [39, 40];

- Based on the various modeling techniques, the platform evaluates the total renewable energy available from various resources; The PSO algorithm determines the distribution of available energy resources [41];

- The total cost of the consumption of electricity and all the above parameters are evaluated every 10 seconds and the GUI is updated. The process continues until the user terminates the platform operation.
Figure 3.7: Flow-chart depicting the functioning of the simulation platform.

For the purpose of illustration, Figure 3.3 also shows a sample screen of an ongoing simulation.
Chapter 4

Resource Modeling

Various models have been developed by researchers to model the different components of HRES [42]. Typically, the models consist of PV panels, Wind Turbine Generators (WTGs), energy storage devices, and grid source, all connected through a control unit to the load.

HRES modeling and control critically depends upon the individual assessment of each component. In order to predict the performance of the overall system, each component is modeled individually and the overall system is evaluated for its capability to meet the demand [17]. Such evaluation assumes that the total sum of the power output from each individual component is accurate enough to meet the total demand [43].

4.1 Modeling of Photovoltaic System

The estimated total solar radiation varies for every month and also depends on position of the sun in the sky. A typical PV panel characteristic for one day is shown in Figure 4.1 [44].
The power output for a PV panel $P$ (in Watts) at a given time can be expressed as [45]:

$$P = \eta_{pv} A_{pv} I_T,$$

(1)

where $\eta_{pv}$ (expressed as percentage) is the efficiency of the PV panel, $A_{pv}$ (in m$^2$) is the area of the PV panel, and $I_T$ (in W/m$^2$) is the total solar radiation incident on the PV surface at the time of calculation. The total energy $PVE$ obtained from a PV system at a given time is:

$$PVE = \sum_{n=1}^{N} P_n * T_{elapsed},$$

(2)

where $P_n$ is the power output of the $n^{th}$ PV panel given by (1), $T_{elapsed}$ is the observation time period given by the difference between the present time and calculation start time and $N$ is the number of PV panels.

### 4.2 Modeling of Wind Turbine System

The energy obtained from a wind turbine system is dependent mainly on the velocity of wind across the turbine. A typical WTG characteristic is shown in Figure 4.2 [46].
Figure 4.2: A typical wind turbine characteristic [46].

Power output $P_w$ (in W/m^2) from a WTG at any given time is [46]:

\[
\begin{align*}
P_w &= \frac{3}{2} V^3 & V & \leq V_c \\
P_w &= 0 & V_c & < V < V_f \\
P_w &= \frac{V_f^3}{V_R^3} V_R^3 & V_R & \leq V \\
P_w &= 0 & V & > V_R
\end{align*}
\]  

(3)

where $a = \frac{3}{2}$, $P_R$ (in W) is the rated power, $V_c$ (in m/sec) is the cut-in velocity, $V_f$ (in m/sec) is the cut-out velocity, and $V_R$ (in m/sec) is the rated velocity of the turbine.

Total power from the wind turbine is given by:

\[
P = P_w \times \eta_w
\]  

(4)

where $A_w$ (in m^2) is the total rotor swept area, and $\eta_w$ (expressed as a percentage) is the efficiency of WTG.

At a given time, the total energy $WTGE$ obtained from a system with several wind turbines is:

\[
WTGE = \sum_{i=1}^{n} P_i t_i
\]  

(5)
where $P_m$ is the power output of the $m^{th}$ wind turbine given by (4), $T_{\text{elapsed}}$ (sec) is the observation time period given by the time difference between the present time and calculation start time, and $M$ is the total number of WTG’s.

### 4.3 Modeling of Energy Storage System

Typically in practice, there exist a variety of energy storage devices including batteries, water pumping, compressed air, fly wheels, ultra-capacitors, etc. Here, the model of a battery has been considered. The maximum energy storage capacity of the battery ($E_b$) is given by [47]:

$$E_b = A_b \times V_b \times$$  \hspace{1cm} (6)

where $A_b$ is the current-hour (given by A-H) rating of the battery, $V_b$ (in Volts) is the maximum voltage of the battery at 100% State-of-Charge (SOC).

To maximize the life of battery, the SOC should not drop below a specified discharge point. The energy available in the battery at the discharge point is defined as the battery energy discharge capacity ($E_{\text{DC}}$). The simulation platform calculates $E_{\text{DC}}$ as:

$$E_{\text{DC}} = SOC_{\text{min}} \times E_b$$ \hspace{1cm} (7)

where $SOC_{\text{min}}$ is the discharge point percentage value.

### 4.4 Total Energy of the System

The total energy obtained from renewable sources of energy (such as solar and wind energy) at an instance of time is given by the sum of equation (2) and (5).
Chapter 5

Home Energy Management

The concept of home energy management demonstrated by the tool comprises of dynamic distributed resource management and optimized operation of household appliances. A heuristic optimization algorithm *i.e.* BPSO is utilized for the optimization of DSM operation of the platform and PSO is utilized for determining the distribution of energy obtained from various sources depending on the load.

5.1 Particle Swarm Optimization

Kennedy and Eberhart first introduced PSO in 1995 as a new heuristic method [48, 49]. PSO is a technique inspired by certain social behaviors exhibited in bird groups and fish schools that is used to explore a search space of a problem definition in order to find particular parameters that are required to maximize a particular objective [50]. The PSO algorithm works by maintaining simultaneously various candidate solutions in the search space. The objective function being optimized evaluates the candidate solution thereby determining the fitness of the solution [51]. Each particle is initialized with a random velocity and position. As the algorithm progresses through its iterations, it evaluates the best fitness of each particle and remembers this as the best individual fitness and its corresponding best
position (particle best solution). Finally, the PSO algorithm maintains the best fitness value achieved among all the particles called the global best fitness and the corresponding global best position (global best solution) [52].

In BPSO, the particles’ personal best and global best positions are updated as in real-valued version. The major difference between BPSO over real-valued version is that velocities of the particles are rather defined in terms of probabilities that a bit will change to ‘1’ [53]. Using this definition, a normalization function is used to restrict the velocity within the range [0, 1] [54]. The normalization function used to obtain the normalized velocity $v'$, is a sigmoid function given by [55]:

$$v' = \frac{\nu}{1 + \frac{\nu}{\nu}}$$

where $\nu$ is the velocity of the particle.

The velocity and position of every particle is updated for all the iterations such that they move towards the optimized solution. The algorithm is stopped after a predefined limiting factor is reached. The various parameters of PSO are defined as:

- Number of particles: the typical range is 20 - 40. Actually for most of the problems 10 particles is large enough to get good results. For some difficult or special problems, one can try 100 or 200 particles as well.
- Dimension of particles: It is determined by the problem to be optimized.
- Range of particles: It is also determined by the problem to be optimized, you can specify different ranges for different dimension of particles.
- Velocity range factors ($v_{\text{max}}$): it determines the maximum possible change for one particle during the iteration.
- Learning factors: usually $c1$ equals to $c2$ and ranges from [0, 4].
The computational complexity of PSO and BPSO is proportional to the number of particles selected for evaluation. Thus, the selection of number of particles for both PSO and BPSO has been done such that the computational times of the algorithms are accommodated within the operational time of the platform, \( i.e. \) the evaluation time of the algorithms does not exceed 10 sec. The exact determination of the computation complexity of the algorithms is outside the scope of this document.

### 5.2 Problem Formulation for Appliance Selection Optimization

The objective of this problem formulation is to determine an effective automated selection of appliances which optimizes the total energy utilization and thus minimize the customer cost of electricity consumption.

#### 5.2.1 Design Objective

- **Objective: Minimizing function definition**

  Total energy consumption of a household is obtained by summing the energy consumptions of all appliances operating in the household. Certain appliances have the feature of having multiple duty cycles. These appliances have the capability to operate for different levels of power consumption. Energy consumption of a given appliance for a particular period of time can be stated as:

\[
E_n = \sum_{\text{present start}}^{t_{\text{present}}} P_n(t) dt,
\]

where \( E_n \) is the energy consumption of the \( n^{th} \) appliance, \( P_n \) is its power consumption, \( t_{\text{present}} \) is the present time, \( t_{\text{start}} \) is the time at which the \( n^{th} \) appliance is set operational.
The cost of electricity consumption of given equipment is dependent on various factors including locality, watts, time of consumption and the cost-rate (peak versus non-peak hour) for that particular time of the day. The cost estimate at a given time \( t \) is:

\[
C_n = \int_{t_{\text{start}}}^{t_{\text{now}}} R(t) * dt,
\]

where \( C_n \) is the cost estimate for the \( n \)th appliance, \( R(t) \) is the cost-rate of electricity for the given locality at time \( t \). The total electricity cost estimate for a household is then given by:

\[
C_{\text{tot}} = \sum_{n=1}^{N} C_n,
\]

where \( N \) is the total number of operational appliances at the time of calculation.

During the course of a day, the completion of operation of all the appliances is mandatory. Therefore, the platform has to monitor and confirm the completion of operation of all the appliances within the duration of 24 hours. This criterion is introduced into the optimization algorithm in the form of \( (M_{\text{tot}} / M_{\text{com}} + \) where the total number of appliances that are selected by the user is \( M_{\text{tot}} \) and the total number of appliances that have completed operation is \( M_{\text{com}} \). As the number of appliances completed during the course of the day increases, the value of \( (M_{\text{tot}} / M_{\text{com}} + \) reduces thereby reducing the functional value of (12).

The minimizing function \( Z_s \) is defined as:

\[
Z_s = \quad + \quad (12)
\]

### 5.2.2 Design Constraints

Due to the operational limits of the intended system, the following constraint should be satisfied throughout the system operation for any feasible solution.
• Constraint 1: Appliance selection criteria

For appliances that are operational throughout the day, if the appliances are not set operational by the optimization algorithm, then $C_{tot}$ is multiplied with a penalty factor which is set as 10,000.

5.2.3 Problem Statement

In summary, the objective of optimum selection of appliances is to minimize the $Z_s$ function.

5.2.4 Data Flow of Optimization Procedure

For the utilization of the BPSO algorithm in the platform, the population size was set to 25 particles, the dimension $d$ was set to the total number of appliances present at the time of calculation, and the maximum number of iterations was set to 100. The minimum velocity $v_{min}$ and maximum velocity $v_{max}$ were set as $-1.0$ and $1.0$ respectively. Acceleration constants $c_1$ and $c_2$ were set as $1$. The inertia weight factor $w_s$ was set as $0.99$. The value of $w_s$ decreases as the iteration number increases [56]:

$$w_s = \frac{w_{max} - w_{min}}{iter_{max} - iter}.$$

(13)

where $iter_{max}$ is the maximum number of iterations, $iter$ is the current iteration number, $w_{max}$ is the maximum value of $w_s$, which is set to $1$, and $w_{min}$ is the minimum value of $w_s$, which is set to $0$. The possible solution space is the defined as $0$ or $1$, which relates to the appliance operational state of switched off and switched on respectively. The computational procedure of the proposed method is laid out as follows:
Step 1: Determine the value of the present cost rate, the total number of operational appliances, the total duration of operation of each appliance and the appliance power consumption across different duty cycles.

Step 2: Randomly generate the particles \( \{ x_i^0, i = 1 \} \), where \( x_i^0 = \ldots, x_{id}^0 \), \( d \) is the dimension, \( x_{id}^0 \) is either 0 or 1.

Step 3: Generate the initial velocities of all particles randomly, \( \{ v_i^0, i = 1 \} \), where \( v_i^0 = \ldots, v_{id}^0 \), \( v_{id}^0 \) is generated randomly with \( v_{id}^0 = + - d \), \( rand \) is a random real number between 0 and 1.

Step 4: For each particle \( i \) in the swarm, set individual best solution \( pbest_i^0 = \ldots \) and using (12), calculate the best fitness value \( pbestValue_i = \ldots \), where \( i = 1, 2, \ldots, N \).

Step 5: Determine the \( pbest_i^0 \) having the best fitness value and assign to global best solution \( gbest \).

Step 6: Increase the iteration number by one.

Step 7: Update the member velocity \( v \) of each particle based on the following equation:

\[
 v_{i+1}^t = + - + - 
\]

where \( i = 1, 2, \ldots, N \) is the number of particles, \( t \) is the iteration number, \( r_1 \) and \( r_2 \) are real random numbers between 0 and 1.

Step 8: Determine the normalized velocity of each particle using the sigmoid function defined in (8):
where \( i = 1, 2, \ldots, N \) is the number of particles and \( t \) is the iteration number.

For each particle, the value of \( v_{i}^{t+1} \) is limited according to the following condition:

\[
v_{i}^{t+1} = \begin{cases} 1 + v_{i}^{t+1} > v_{i}^{t+1} < \end{cases}
\]

(16)

- Step 9: Update the member position \( x \) of each particle based on the following equation:

\[
x_{i}^{t} = \begin{cases} x_{i}^{t+1} > \end{cases} \]

(17)

where \( i = 1, 2, \ldots, N \) is the number of particles, \( t \) is the iteration number, and \( rand_{i} \) is a random real number between 0 and 1.

- Step 10: Calculate value of the design objective (12) and evaluate the fitness of each particle.

- Step 11: If the fitness of the particle is better than the value stored in \( pbest \), update \( pbest \) with the present values of the particle.

- Step 12: Repeat step 4 for each particle.

- Step 13: Determine the best solution for all the particles and update \( gbest \).

- Step 14: Update the inertia weight factor \( w \).

- Step 15: If the maximum number of iterations reaches the predefined limiting factor, then exit BPSO algorithm, otherwise repeat step 4.
5.3 Problem Formulation for Resource Management Optimization

The objective of this problem formulation is to determine an effective distribution of energy from various renewable sources between the charging of battery and utilization by appliances.

5.3.1 Design Objective

- Objective: Minimizing function definition

At a given time, the total cost of electricity consumption for all the appliances in a household is given by:

$$ F(x) = - - + * CR \quad , \quad (18) $$

where $x$ is the optimization parameter, $E$ is the total energy consumption by all the appliances, $CR$ is the cost-rate at the time of calculation, $PVE$ is the total available solar energy at the time of calculation, and $WTGE$ is the total available wind energy at the time of calculation. It is assumed that during the highest cost rate time period of the day, the complete energy available from the renewable sources including the energy storage battery is utilized by the appliances. After the utilization of battery during high cost periods, it has to be recharged during the course of the day. At any instance, the amount of energy used to recharge the battery is given by $x^*(PVE + WTGE)$. The difference between the maximum capacity of the battery and the amount available at a given instance during recharge is given by:

$$ G(x) = - + + \quad , \quad (19) $$

where $E_b$ is the maximum battery capacity and $E_{ba}$ is the battery energy available at the time of calculation.

The combined minimizing function $Z_r$ is defined as:
\[ Z_r = \quad + \quad \] (20)

### 5.3.2 Design Constraints

Due to the operational limits of the intended system, there are a set of constraints that should be satisfied throughout the system operation for any feasible solution.

- **Constraint 1: Value of \( x \)**
  
  At any time instance, the value of \( x \) is a percentage value. Hence the range of \( x \) is given as:
  
  \[ 0 \leq \quad \leq \quad (21) \]

- **Constraint 2: Total charge of battery**
  
  During the recharging of the battery, the sum of total energy used to recharge the battery and the prior energy available in the battery cannot be greater than the total capacity of the battery, \( i.e. \)
  
  \[ E_n - \quad + \quad \geq \quad (22) \]

  If constraint (22) is not satisfied, the obtained solution \( x \) is invalid and has to be discarded. To achieve this, the minimizing function is multiplied with a penalty factor which is set to 1,000,000.

### 5.3.3 Problem Statement

In summary, the objective of optimum distribution of energy is to calculate the value of \( x \) for minimizing \( Z_r \), subject to the constraints (21) and (22). For each optimization run, the value of the total energy consumed by the appliances, the total renewable energy available, the cost rate, and the energy stored in the battery changes. Thus the value of \( x \) is not constant.
5.3.4 Data Flow of Optimization Procedure

For the utilization of the PSO algorithm in the platform, the population size was set to 30 particles and the maximum number of iterations was set to 100. Acceleration constants $c_1$ and $c_2$ were set as 1. Initial weight factor $w$ was set to 0.99. The value of $w$ decreases as the iteration number increases [56]:

$$w = w_{\text{max}} / \text{iter}_{\text{max}},$$

(23)

where $\text{iter}_{\text{max}}$ is the maximum number of iterations, $\text{iter}$ is the current iteration number, $w_{\text{max}}$ is the maximum value of $w$, which is set to 1, and $w_{\text{min}}$ is the minimum value of $w$, which is set to 0. The possible solution space is defined as values between 0 and 1 which relates to the percentage distribution of resources. The computational procedure of the proposed method is laid out as follows:

- **Step 1:** Specify the lower and upper bounds of the value of $x$. Determine the value of the present instance of solar energy, wind energy, energy available stored in the battery, total capacity of the battery, total energy consumed by all appliances, and the present cost rate.

- **Step 2:** Randomly generate the particles with random velocity and position within the possible solution space.

- **Step 3:** Initialize the individual best solution $p_{\text{best}}$ for each particle and the global best solution $g_{\text{best}}$.

- **Step 4:** Calculate values of the design objective (20) and evaluate the fitness of each particle.

- **Step 5:** If the fitness of the particle is better than the value stored in $p_{\text{best}}$, update $p_{\text{best}}$ with the present values of the particle.
- Step 6: Repeat step 5 for each particle.

- Step 7: Determine the best solution for all the particles and update $g_{best}$.

- Step 8: Increase the iteration number by one.

- Step 9: Update the member velocity $v$ of each particle based on the following equation:

\[
v_{i}^{t+1} = v_{i}^{t} + w_{i}^{t} * c_{r} * p_{best}^{t} + c_{r} * g_{best}^{t}
\]

where $i = 1, 2, ..., N$ is the number of particles and $t$ is the iteration number.

- Step 10: Update the member position of each particle based on the following equation:

\[
x_{i}^{t+1} = x_{i}^{t} + v_{i}^{t+1}
\]

where $i = 1, 2, ..., N$ is the number of particles and $t$ is the iteration number.

- Step 11: Update the inertia weight factor $w_{i}$.

- Step 12: If the maximum number of iterations reaches a predefined limiting factor, then exit PSO algorithm, otherwise repeat step 4.
Chapter 6

Energy Consumption and Cost Analysis

For evaluating the platform, the following sample household appliances were considered as shown in Table 6.1. For appliances with multiple duty-cycle operation, the variation in their peak power consumption is shown. The properties (name, number, time of operation, and power consumption) of the appliances were set as shown in Table 6.1. The platform has been evaluated for various scenarios. These scenarios have been discussed below in detail.

6.1 Scenario 1

In scenario 1, the cost of energy consumed without DSM is compared to that obtained from the proposed DSM simulation platform for various scenarios. Evaluation was done for two seasons i.e. Summer and Winter. While Summer was considered to extend from April 1 to September 30, Winter was considered to extend from October 1 to March 31. For summer, the following appliances are considered to be operational: lighting, washing machine, clothes dryer, water heater, swimming pool pump, refrigerator, air conditioner, television, CD player, computer, microwave, and dishwasher.
<table>
<thead>
<tr>
<th>Appliance Name</th>
<th>Number of Appliances</th>
<th>Time of Operation</th>
<th>Time of Operation Without DSM</th>
<th>Consumption (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Conditioner</td>
<td>3</td>
<td>Full Day</td>
<td>Full Day</td>
<td>3500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>Clothes Dryer</td>
<td>1</td>
<td>120 mins</td>
<td>9pm - 11pm</td>
<td>650</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>1</td>
<td>180 mins</td>
<td>9am - 10am</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9pm - 11pm</td>
<td>1200</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>2</td>
<td>Full Day</td>
<td>Full Day</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>600</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>450</td>
</tr>
<tr>
<td>Pool Pump</td>
<td>1</td>
<td>240 mins</td>
<td>4pm - 8pm</td>
<td>2000</td>
</tr>
<tr>
<td>CD Player</td>
<td>1</td>
<td>User Defined</td>
<td>User Defined</td>
<td>250</td>
</tr>
<tr>
<td>Computer</td>
<td>1</td>
<td>User Defined</td>
<td>User Defined</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td>Electric Heater</td>
<td>8</td>
<td>Full Day</td>
<td>Full Day</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td>Lighting</td>
<td>30</td>
<td>Season Dependent</td>
<td>Season Dependent</td>
<td>60</td>
</tr>
<tr>
<td>Microwave</td>
<td>2</td>
<td>User Defined</td>
<td>User Defined</td>
<td>1000</td>
</tr>
<tr>
<td>Television</td>
<td>3</td>
<td>User Defined</td>
<td>User Defined</td>
<td>300</td>
</tr>
<tr>
<td>Vacuum Cleaner</td>
<td>1</td>
<td>User Defined</td>
<td>User Defined</td>
<td>250</td>
</tr>
<tr>
<td>Washing Machine</td>
<td>1</td>
<td>60 mins</td>
<td>8pm - 9pm</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6am - 11am</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>700</td>
</tr>
<tr>
<td>Water Heater</td>
<td>1</td>
<td>Full Day</td>
<td>6pm - 1am</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11am - 6pm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>500</td>
</tr>
</tbody>
</table>
For the user-defined appliances, the following operational times periods have been defined as:

- Lighting is considered to be operational from 6 am to 8 am and from 8 pm to midnight.

- Television and CD player are considered to be operational from 8 pm to midnight, microwave for 1 hour, and computer from 6 pm to 9 pm.

For winter, the evaluation is done for the following appliances: lighting, washing machine, clothes dryer, water heater, refrigerator, electric heater, television, CD player, computer, microwave, and dishwasher. For the user-defined appliances, the following operational time periods have been defined:

- Lighting is considered to be operational from 5 pm to midnight and from 6 am to 10 am.

- Television and CD player are considered to be operational from 8 pm to midnight, microwave for 1 hour, and computer from 6 pm to 9 pm.

The operability of the platform has been tested for the following criteria:

- Different cost-rate structures.

- Different customer preferences.

6.1.1 Results Based on Cost-Rate Structures

The evaluation of the platform was performed for two cost-rate structures. The aim of these results is to show the cost reduction of energy consumption with the platform compared to that of without the platform. Sample priorities of the appliances used in the simulation are shown in Table 6.2.
Case 1: Here, the cost-rates for electricity are assumed to have a standard fixed cost-rate for on-peak and off-peak time periods. Definitions of start and stop times during on-peak and off-peak times come from Table 6.3.

Table 6.3: Peak/Off-Peak Time and Cost for Case 1 (Scenario 1).

<table>
<thead>
<tr>
<th>Time</th>
<th>Cost (c/Kwh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-Peak Hours</td>
<td>7 am to 11 pm</td>
</tr>
<tr>
<td>Off-Peak Hours</td>
<td>11 pm to 7 am</td>
</tr>
</tbody>
</table>

The results obtained for case 1 are shown in Tables 6.4 and 6.5.

Table 6.4: Results of Case 1 for 1 Day in Summer season (Scenario 1).

<table>
<thead>
<tr>
<th>Testing Conditions</th>
<th>Cost ($/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DSM</td>
<td>1.38</td>
</tr>
<tr>
<td>With DSM</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Percentage cost saving per day in Summer using DSM: (1.38 – 1.22)/1.38 = 11.59%.

Percentage cost saving per day in Winter using DSM: (1.96 – 1.75)/1.96 = 10.71%.
Table 6.5: Results of Case 1 for 1 Day in Winter Season (Scenario 1).

<table>
<thead>
<tr>
<th>Testing Conditions</th>
<th>Cost ($/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DSM</td>
<td>1.96</td>
</tr>
<tr>
<td>With DSM</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Case 2: For case 2, the cost-rates for electricity were assumed to be part of a cost-rate structure plan as shown in Table 6.6.

Table 6.6: Cost-Rate Plan for Case 2 (Scenario 1).

<table>
<thead>
<tr>
<th>Time</th>
<th>Cost (c/Kwh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 am to 9 am</td>
<td>0.45</td>
</tr>
<tr>
<td>9 am to 4 pm</td>
<td>0.30</td>
</tr>
<tr>
<td>4 pm to 6 pm</td>
<td>0.37</td>
</tr>
<tr>
<td>6 pm to 10 pm</td>
<td>0.45</td>
</tr>
<tr>
<td>10 pm to 7 am</td>
<td>0.30</td>
</tr>
</tbody>
</table>

The results obtained for case 2 are shown in Tables 6.7 and 6.8.

Table 6.7: Results of Case 2 for 1 Day in Summer Season (Scenario 1).

<table>
<thead>
<tr>
<th>Testing conditions</th>
<th>Cost ($/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DSM</td>
<td>1.18</td>
</tr>
<tr>
<td>With DSM</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Percentage cost saving per day in Summer using DSM: \((1.18 - 0.82)/1.18 = 30.51\%\).

Percentage cost saving per day in Winter using DSM: \((1.63 - 1.17)/1.63 = 28.22\%\).
Table 6.8: Results of Case 2 for 1 Day in Winter Season (Scenario 1).

<table>
<thead>
<tr>
<th>Testing conditions</th>
<th>Cost ($/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DSM</td>
<td>1.63</td>
</tr>
<tr>
<td>With DSM</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Comparing results of energy consumption using cost-rate plan of case 2 with DSM and that of case 1 without DSM leads to following conclusion:

- For Summer, percentage cost savings are 40.58%.
- For Winter, percentage cost savings are 40.31%.

6.1.2 Results Based on Customer Preferences

In order to evaluate the platform for different customer preferences, the cost-rate plan in Table 6.6 was considered along with the customer preferences in Table 6.2 and Table 6.9.

Table 6.9: Type 2 Customer Preference Settings in the Form of Priority (Scenario 1).

<table>
<thead>
<tr>
<th>Appliance name</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing Machine</td>
<td>3</td>
</tr>
<tr>
<td>Lighting</td>
<td>2</td>
</tr>
<tr>
<td>Clothes Dryer</td>
<td>4</td>
</tr>
<tr>
<td>Water Heater</td>
<td>7</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>8</td>
</tr>
<tr>
<td>Pool Pump</td>
<td>5</td>
</tr>
<tr>
<td>Air Conditioner/Electric Heater</td>
<td>6</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>1</td>
</tr>
</tbody>
</table>

The results obtained for Table 6.2 are shown in section 6.1.1 and for Table 6.9 are shown in Tables 6.10 and 6.11.
Table 6.10: Results (Customer Preferences) Obtained for 1 Day in Summer Season (Scenario 1).

<table>
<thead>
<tr>
<th>Testing Conditions</th>
<th>Cost ($/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DSM</td>
<td>1.18</td>
</tr>
<tr>
<td>With DSM</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Percentage cost saving per day in Summer using DSM: \( \frac{1.18 - 0.96}{1.18} = 19.49\% \).

Table 6.11: Results (Customer Preferences) Obtained for 1 Day in the Winter Season (Scenario 1).

<table>
<thead>
<tr>
<th>Testing Conditions</th>
<th>Cost ($/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DSM</td>
<td>1.63</td>
</tr>
<tr>
<td>With DSM</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Percentage cost saving per day in Winter using DSM: \( \frac{1.63 - 1.35}{1.63} = 17.17\% \).

On comparing the results obtained for change in preferences from Table 6.2 to Table 6.9, the percentage cost savings were determined to be about 11% for both Summer and Winter seasons.

6.2 Scenario 2

The platform was evaluated for the operation of the appliance selection optimization algorithm. Sample priorities of the appliances considered to be operational are shown in Table 6.12. The platform was operated without the utilization of renewable sources of energy. The daily cost-rates for consumption of electricity were assumed to be part of a cost-rate structure plan shown in Table 6.6.
Table 6.12: Customer Preference Settings in the Form of Priority (Scenario 2).

<table>
<thead>
<tr>
<th>Appliance Name</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing Machine</td>
<td>5</td>
</tr>
<tr>
<td>Clothes Dryer</td>
<td>6</td>
</tr>
<tr>
<td>Water Heater</td>
<td>3</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>4</td>
</tr>
<tr>
<td>Pool Pump</td>
<td>7</td>
</tr>
<tr>
<td>Air Condition/Electric Heater</td>
<td>2</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>1</td>
</tr>
</tbody>
</table>

Based on the cost-rate plan defined, the results obtained for scenario 2 are shown in Table 6.13.

Table 6.13: Results Obtained for 1 Day (Scenario 2).

<table>
<thead>
<tr>
<th>Testing Conditions</th>
<th>Cost ($/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DSM and without optimized appliance selection</td>
<td>1.31</td>
</tr>
<tr>
<td>With DSM and without optimized appliance selection</td>
<td>0.887</td>
</tr>
<tr>
<td>With DSM and with optimized appliance selection</td>
<td>0.877</td>
</tr>
</tbody>
</table>

Percentage cost saving of utilizing DSM and optimized selection: \( \frac{(1.31 - 0.877)}{1.31} = 33.1\% \).

### 6.3 Scenario 3

The platform was evaluated for the operation of renewable energy resource management. The operational appliances are shown in Table 6.12. The specifications for the renewable energy resources were set as follows:
Energy storage (battery): Current rating – 220 A·H, voltage – 48 V, \( SOC_{\text{min}} \) – 40%.

Solar panel: Area – 20\( \text{m}^2 \), efficiency – 12.5%.

Wind turbine: Rotor diameter – 4.75 m, \( V_C \) = 2 m/sec, \( V_R \) = 8 m/sec, \( V_F \) = 15 m/sec, turbine efficiency – 35%.

Renewable energy sources

Cost cut-off: 0 c/Kwh

During the platform evaluation, the PV panel and wind turbine product and installation charges were not considered during evaluation. Also, for the condition of non utilization of optimized resource management, during peak hour, the energy available from renewable sources of energy and energy storage was utilized to power the appliances. During off-peak hour, all the energy available from solar and wind is utilized to charge the energy storage. To determine cost savings, the platform has been evaluated for two different days of a year.

Day 1: The solar insolation data and wind speed data utilized during for evaluating the platform are shown in Table 6.14 and Table 6.15 respectively. These data were obtained from [39] and [40] respectively.

Table 6.14: Solar Insolation (Radiation) Values (Day 1).
Table 6.15: Wind Speed Values (Day 1).

<table>
<thead>
<tr>
<th>Hour of Day</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed (Kmph)</td>
<td>45.2</td>
<td>16.8</td>
<td>5.9</td>
<td>34.4</td>
<td>20.7</td>
<td>27.2</td>
<td>36.8</td>
<td>12.2</td>
</tr>
<tr>
<td>Hour of Day</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>Wind Speed (Kmph)</td>
<td>6.5</td>
<td>37.6</td>
<td>3.0</td>
<td>31.6</td>
<td>19.7</td>
<td>44.2</td>
<td>11.3</td>
<td>11.4</td>
</tr>
<tr>
<td>Hour of Day</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>Wind Speed (Kmph)</td>
<td>13.7</td>
<td>27.6</td>
<td>34.9</td>
<td>20.9</td>
<td>31.1</td>
<td>3.24</td>
<td>35.1</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Based on the cost-rate plan defined in Table 6.6, the results obtained for day 1 are shown in Table 6.16.

Table 6.16: Results Obtained for Day 1 (Scenario 3).

<table>
<thead>
<tr>
<th>Testing Conditions</th>
<th>Cost ($/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without optimized resource management and without optimized appliance selection</td>
<td>0.269</td>
</tr>
<tr>
<td>With optimized resource management and without optimized appliance selection</td>
<td>0.225</td>
</tr>
<tr>
<td>With optimized resource management and with optimized appliance selection</td>
<td>0.218</td>
</tr>
</tbody>
</table>

Percentage cost saving per day by utilizing optimized resource management: \((0.269 - 0.225)/0.269 = 16.3\%\).

Percentage cost saving per day by utilizing optimized appliance selection and optimized resource management: \((0.269 - 0.218)/0.269 = 18.95\%\).

Day 2: The solar insolation data and wind speed data utilized are shown in Table 6.17 and Table 6.18 respectively. These data were obtained from [39] and [40] respectively.
Table 6.17: Solar Insolation (Radiation) Values (Day 2).

<table>
<thead>
<tr>
<th>Hour of Day</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insolation (W/m²)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16</td>
<td>116</td>
<td>409</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hour of Day</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insolation (W/m²)</td>
<td>629</td>
<td>808</td>
<td>946</td>
<td>1081</td>
<td>1091</td>
<td>1041</td>
<td>1058</td>
<td>928</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hour of Day</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insolation (W/m²)</td>
<td>677</td>
<td>470</td>
<td>257</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Based on the cost-rate plan defined in Table 6.6, the results obtained for day 2 are shown in Table 6.19.

Table 6.18: Wind Speed Values (Day 2).

<table>
<thead>
<tr>
<th>Hour of Day</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed (Kmph)</td>
<td>39.9</td>
<td>41.4</td>
<td>41.1</td>
<td>36.0</td>
<td>21.5</td>
<td>24.2</td>
<td>30.6</td>
<td>40.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hour of Day</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed (Kmph)</td>
<td>15.01</td>
<td>25.8</td>
<td>4.6</td>
<td>4.3</td>
<td>24.26</td>
<td>42.9</td>
<td>28.6</td>
<td>43.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hour of Day</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed (Kmph)</td>
<td>13.6</td>
<td>30.2</td>
<td>50.12</td>
<td>30.6</td>
<td>440.2</td>
<td>37.0</td>
<td>6.9</td>
<td>28.6</td>
</tr>
</tbody>
</table>

Table 6.19: Results Obtained for Day 2 (Scenario 3).

<table>
<thead>
<tr>
<th>Testing Conditions</th>
<th>Cost ($/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without optimized resource management and without optimized appliance selection</td>
<td>0.236</td>
</tr>
<tr>
<td>With optimized resource management and without optimized appliance selection</td>
<td>0.196</td>
</tr>
<tr>
<td>With optimized resource management and with optimized appliance selection</td>
<td>0.187</td>
</tr>
</tbody>
</table>
Percentage cost saving per day by utilizing optimized resource management: \( \frac{0.236 - 0.196}{0.236} = 16.9\% \).

Percentage cost saving per day by utilizing optimized appliance selection and optimized resource management: \( \frac{0.236 - 0.187}{0.236} = 20.7\% \).
Chapter 7

Conclusions and Future Work

7.1 Conclusions

The century old electric grid is in the midst of major infrastructural modifications to address future demands. In the past ten years, there have been noticeable changes in the electricity industry. These changes include utilizing different fuels and technologies for generating electricity and reducing power-plant emissions, implementing various methods for regulating utility planning and cost-rates, reducing electricity prices, adding bidirectional communication between consumer and utility, etc.

As utilities play a stronger role in the electricity market, the use of dynamic pricing can encourage energy savings at certain time periods by identifying time periods which are expensive for electricity production by means of sending real-time cost-rates to the end user. Time and location dependent prices will send powerful signals to consumers that will encourage energy savings when and where electricity is expensive to produce/deliver. Utilities themselves are increasingly using DSM as customer-service programs to maintain and build market share.

DR is increasingly being recognized as a reliable and cost-effective technique to meet increasing power demands. Each of the DR programs provides a different type of service
tailored to the demand of various classes of consumers, thereby providing a cost-effective and environmentally friendly solution.

A new GUI based platform for developing, testing, and investigating the consumer-based DSM is presented in the document. It complements the research being done for developing commercial products, such as smart homes, thus providing an excellent interface for the end-user to evaluate the performance and possible benefits of DSM. The platform simulates a household environment, thereby providing the customer with a real-time analysis of optimized appliance selection and resource management. The platform can be used for extending research on improving DSM and for educational purposes. The platform also has been demonstrated as a classroom tool for DSM.

The platform was evaluated for various scenarios. A household can have cost savings up to 12% by the utilization of DSM in a regular cost plan and up to 31% by the utilization of DSM in a TOU cost-rate plan initiative. These results indicate that utilization of DSM for a regular plan or cost-rate plan reduces the total cost of electricity consumption. The efficiency of the platform is dependent on the cost-rate plan and the number of appliances that are being automated. The user operated appliances (e.g. Television, CD player, etc.) do not contribute towards the end-user cost savings.

During the priority-based appliance selection operation of the platform, cost savings of up to 19% can be achieved by a smart selection by the end-user. The results also indicate the change in the total cost of electricity consumption with respect to the customer preference selected. An intelligent choice of appliance preferences results in the reduction of total electricity consumption cost for the user.

The utilization of DSM and BPSO for appliance selection helps to achieve a cost saving of 33% for the end-user. The results show that optimized resource management leads to a
cost saving of 16-17%. The results also show that utilizing optimized appliance selection and optimized resource management together leads to a cost saving of about 19-21%.

The end user can obtain maximum benefit by utilizing DSM, BPSO for appliance operation selection and optimized resource management. If the power demand for a household is on the higher side and if the cost difference between the peak and off-peak hours in the cost-rate plan is large, the annual cost savings will be more significant.

7.2 Future Work

The various encouraging results obtained from the platform indicate the following possible upgrades to the platform.

- The platform provides the option of selecting from fixed available cost-rate plans. The platforms for each household, when interconnected through internet, can create a WAN. During real-time operation the platforms can exchange data to determine the energy consumption for a given area as a whole. This provides an opportunity for determining real-time dynamic pricing for the load across the selected area.

- The computational complexity of the optimization algorithms can be evaluated extensively for the given problem definition and the individual algorithm parameters can be modified to improve the performance of the respective algorithm.

- The platform performance can be evaluated by utilizing other optimization techniques for appliance selection and for resource management. These optimization techniques can include Genetic Algorithm, Ant Colony Optimization, Fuzzy Systems, Support Vector Machines, etc. A comparative study can be conducted to evaluate the computational time for various optimization techniques.
● The platform can be enhanced such that prior data regarding household electricity usage can be considered for probabilistic determination of present and future consumption of electricity. The electricity consumption pattern can be analyzed for an end-user to evaluate better consumption patterns to increase the cost savings.

● The probabilistic determination of present and future consumption of electricity, along with the product and installation charges of renewable resources, can be utilized to evaluate the break-even time for the end user.

● The total number of end users will increase as the usability of the platform is simplified. The visual composition and temporal behavior of the GUI can be improved to increase the overall usability of the platform.

● The database of appliances available can be integrated with those available from large-scale manufacturers (e.g. General Electric, Whirlpool, Electrolux, etc.) to provide more selection options for the end-users.

● The concept of using Plug-in Hybrid Electric Vehicles (PHEVs) for storing energy can be integrated into the platform along with the concept of selling back excess energy to the grid.
References


Appendix A

Various Screenshots of Simulation Platform

A.1 Cost-rate/Program Selector Window (User-Defined)

Figure A.1: Screenshot of user-defined selection of cost-rate/program selector window.
A.2 Renewable Sources Window (User-Defined)

Figure A.2: Screenshot of user-defined selection of renewable sources window.
A.3 Appliances Property Window (User-Override)

![Enter Appliance Property window with User Override and Multiple Duty Cycle selected]

Figure A.3: Screenshot of user override of appliances property window.

A.4 Appliances Property Window (Multiple Duty Cycle)

![Enter Appliance Property window with Multiple Duty Cycle selected]

Figure A.4: Screenshot of multiple duty cycle of appliances property window.
A.5 Appliances Property Window (Manual Selection)

Figure A.5: Screenshot of manual selection of appliances property window.

A.6 Appliances Property Window (Manual Selection with Multiple Duty Cycle)

Figure A.6: Screenshot of manual selection with multiple duty cycle of appliances property window.
A.7 Appliances Property Window (Manual Selection with User Override)

![Screenshot of manual selection with user override of appliances property window.](image)

Figure A.7: Screenshot of manual selection with user override of appliances property window.
A.8 Graphical User Interface of the Simulation Platform when Reset

Figure A.8: Screenshot of graphical user interface when reset.
Appendix B

Source Code for Optimization Algorithms

B.1 Source Code for Appliance Selection Optimization Algorithm

```java
int populationSize = 25; int iterations = 100;
Vector<Integer> gBest = new Vector<Integer>();
gBest.setSize(dimension);
double gBestValue = 10000000.0;
double result = 0.0;
Random randomNumber = new Random();
double r1 = randomNumber.nextDouble();
double r2 = randomNumber.nextDouble();
double c1 = 1;
double c2 = 1;
double w = 0.99;
double vMax = 1.0;
double vMin = -1.0;
Vector<bParticle> swarm = new Vector<bParticle>();

for (int x=0; x< populationSize;x++) {
    bParticle p = new bParticle();
    for (int y=0;y<dimension;y++) {
        p.pos.addElement(randomNumber.nextInt(2));
        p.vel.addElement(vMin + (vMax - vMin)*randomNumber.nextDouble());
        p.pbestValue = 10000000;
    }
    swarm.addElement(p);
}
double avgSolution = calAvgEnergy();
for (int count = 0; count < iterations; count ++){
    for (int x = 0;x < swarm.size();x++) {
        result = func(swarm.get(x).pos, CostRate, MDCValues, avgSolution);
        if(result < swarm.get(x).pbestValue) {
            // Update pbest values here
        }
    }
}
```

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swarm.get(x).pBest = (Vector<Integer>)
    swarm.get(x).pos.clone();
swarm.get(x).pbestValue = result;
}
if(result < gBestValue){
gBest = (Vector<Integer>) swarm.get(x).pos.clone();
gBestValue = result;
}
}
for(int x =0;x < swarm.size();x++){
    for(int y=0;y<dimension;y++){
        double newV = (w * swarm.get(x).vel.get(y) + c1 * r1 *
            (swarm.get(x).pBest.get(y) - swarm.get(x).pos.get(y))
        + c2*r2*(gBest.get(y) - swarm.get(x).pos.get(y)));
        newV = sigMoid(newV);
        if(newV > vMax) {
            newV = vMax;
        } else if(newV < vMin) {
            newV = vMax;
        }
        swarm.get(x).vel.set(y, newV);
        if( newV > randomNumber.nextDouble()) {
            swarm.get(x).pos.set(y, 1);
        } else {
            swarm.get(x).pos.set(y, 0);
        }
    }
}
return gBest;

private double sigMoid(double v) {
    return 1/(1+Math.exp(-v));
}

private int decode(Vector<Integer> c, int MDCValue,int count) {
    int sum = 0, n = 1;
    if(MDCValue == 1){
        for(int i = 0;i < 2; i++) {
            if(c.get(count) == 1) {
                sum = sum + n;
            }
            count++;
            n = n * 2;
        }
    }
private double calAvgEnergy() {
    double TE = 0.0;
    for (int i = 0; i < cost.length; i++) {
        TE = TE + (cost[i] * timeValuesRetrieve[i] / 60);
    }
    TE = TE * CostRate;
    return TE / 24;
}

private double func(Vector<Integer> currentSolution, double CR1, int[] MDCValues, double avgSolution) {
    int NAcomplete = getNumberApplianceComplete();
    int TotalAppliances = getMaxID();
    double sum = 0.0;
    int count = 0;
    for (int i = 0; i < MDCValues.length; i++) {
        if (MDCValues[i] == 1) {
            int decodeValue = decode(currentSolution, 1, count);
            /* adding a penalty function to so that appliances running through the day are always switched on*/
            if (timeValues.get(i) == 1440 && (decodeValue == 0)) {
                sum = sum * 10000;
                break;
            }
            if (decodeValue == 1) {
                sum = sum + (CostRate * energyValues.get(i));
            }
            else if (decodeValue == 2) {
                sum = sum + (CostRate * energyValues1.get(i));
            }
            else if (decodeValue == 3) {
                sum = sum + (CostRate * energyValues2.get(i));
            }
            count += 2;
        }
        else {
            if (currentSolution.get(count) == 1) {
                sum = sum + (CostRate * energyValues.get(i));
            }
            count++;  
        }
    }
}

return sum;
}
sum = sum * Math.pow(TotalAppliances/(NAcomplete + 1), 2);

return sum;
}

B.2 Source Code for Resource Management Optimization Algorithm

int populationSize = 30; int dimension = 1; int iterations = 100;
Vector<Double> gBest = new Vector<Double>();
gBest.setSize(dimension);
double gBestValue = 1e15;
double result = 0.0;
Random randomNumber = new Random();
double r1 = randomNumber.nextDouble();
double r2 = randomNumber.nextDouble();
double c1 = 1;
double c2 = 1;
double w = 0.99;
double vMax = 1.0;
double vMin = -1.0;
double xMin = 0;
double xMax = 1;
Vector<Particle> swarm = new Vector<Particle>();

for(int x=0; x< populationSize;x++)
{
    Particle p = new Particle();
    for(int y=0;y<dimension;y++)
    {
        p.pos.addElement(randomNumber.nextDouble());
        p.vel.addElement(randomNumber.nextDouble());
        p.pbestValue = 1e15;
    }
    swarm.addElement(p);
}

for(int count = 0; count < iterations; count ++)
{
    for (int x=0;x < swarm.size();x++)
    {
        result = f1Real(swarm.get(x).pos,maxEnergyStorageOutput,
costEnergyCalValue,totalRenEnergy,energyStorageAvailEnergy,hourrate);
        if(result < swarm.get(x).pbestValue)
        {
            swarm.get(x).pBest = (Vector<Double>)swarm.get(x).pos.clone();
            swarm.get(x).pbestValue = result;
        }
    }
    if(result < gBestValue)
    {
        gBest = (Vector<Double>)swarm.get(x).pos.clone();
gBestValue = result;
    }
}

for(int x =0;x < swarm.size();x++)
{
    for(int y=0;y<dimension;y++)
    {
double newV = (w * swarm.get(x).vel.get(y) + c1 * r1 * 
(swarm.get(x).pBest.get(y) - swarm.get(x).pos.get(y)) 
+ c2*r2*(gBest.get(y)-swarm.get(x).pos.get(y)));

if(newV > vMax){
    newV = vMax;
} else if(newV < vMin){
    newV = vMax;
}

swarm.get(x).vel.set(y, newV);
swarm.get(x).pos.set(y, 
    swarm.get(x).vel.get(y)+swarm.get(x).pos.get(y));

if(swarm.get(x).pos.get(y)>xMax){
    swarm.get(x).pos.set(y, xMax);
} else if(swarm.get(x).pos.get(y) < xMin){
    swarm.get(x).pos.set(y, xMin);
}
}
return gBest.get(0);

private double f1Real(Vector<Double> currentSolution, double maxEnergyStorageOutput, double energyConsumptionValue2, double totalRenEnergy2, long energyStorag, float hourrate) {  
    double f = 0;
    double x,y;
    double penFunc = 1e6;
    for(int i =0; i<currentSolution.size();i++)
    {
        x = (energyConsumptionValue2 - ((1-currentSolution.get(i)) * totalRenEnergy2))*hourrate;
        y = maxEnergyStorageOutput - (energyStorageAvailEnergy + currentSolution.get(i) * totalRenEnergy2);
        /* adding a penalty function */
        if(y < 0){
            f = penFunc * Math.sqrt((x*x) + (y*y));
        } else {
            f = Math.sqrt((x*x) + (y*y));
        }    
    }
    return f;
}