Residential DERs in Service-Oriented Load Participation: Enhancing Grid Flexibility

Zhongkai Zeng
Portland State University

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Residential DERs in Service-Oriented Load Participation: Enhancing Grid Flexibility

by

Zhongkai Zeng

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science
in
Electrical and Computer Engineering

Thesis Committee:
Robert Bass, Chair
John M. Acken
Jonathan Bird

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Abstract

Amidst concerns about power consumption during peak periods and potential grid instability, the role of Distributed Energy Resource (DER) aggregation comes into consideration. Smart electric water heaters with remote capabilities and energy storage offer load reduction capabilities that can help maintain grid stability and manage residential energy consumption. DERs address challenges posed by stochastic renewable energy generation and fossil fuel power plant emissions, playing a contributing role in load shifting and enhancing grid flexibility by participating in energy management programs.

However, high unenrollment rates in demand response programs, notably programs that use direct load control, persist due to customer dissatisfaction. To tackle this challenge, utilities can adopt a customer-centric approach to optimize program participation and ensure grid reliability. Engaging customers in program design reduces unenrollment rates and increases customer enrollment, promoting sustainable energy practices and grid stability.

In navigating the complexities of peak power usage, utilities must prioritize customer satisfaction to sustain grid resilience. By fostering a supportive environment and actively involving customers in program implementation,
utilities can address concerns surrounding direct load control and other methods. This approach not only enhances program participation but also strengthens the relationship between utilities and consumers, ultimately promoting sustainable energy practices and grid stability.

The objective of this work is to explore an innovative approach to demand response through the use of Service-Oriented Architecture. By implementing this framework, customers gain increased flexibility to actively participate in demand response programs at their convenience. Simultaneously, utilities engage in grid-DER service practices on customer DERs to conduct energy management. The primary focus of this work involves demonstrating the application of grid-DER service principles on physical DERs, and assessing its practicality within the grid-DER service context. Subsequently, the work extends to the development of a modeling environment, enabling a comparative analysis between the outcomes of physical DERs and their simulated counterparts. This investigation aims to contribute insights into the effectiveness and viability of grid-service strategies in optimizing demand response programs.
To Coffee, Energy Drinks and Late Nights: "Dedicated to coffee, and Bang energy drink for its unwavering support during those late-night writing sessions, and to my comfy bed, for understanding when I couldn’t spend much time with it."
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To my family, thank you for the constant support and always be there for me. Also, always listen to my conversation regarding to my research topics even though I kind of force you to.

To the U.S Army, thank you for teaching me "attention to detail and teamwork is the key".
Contents

Abstract i

Dedication iii

Acknowledgements iv

List of Tables vii

List of Figures viii

1 Introduction 1
  1.1 Problem Statement .............................................. 1
  1.2 Objectives of Work ........................................... 3
  1.3 Literature Summary ........................................... 6
    1.3.1 CTA-2045 Communication .................................... 6
    1.3.2 Demand Response .......................................... 8
    1.3.3 Grid-Service Definition .................................... 10
  1.4 Energy Grid of Things ......................................... 13

2 Design Methodology 15
  2.1 Objective .................................................. 15
  2.2 Energy Grid of Things Configuration ........................ 15
    2.2.1 DER Set-up .............................................. 16
    2.2.2 DERMS Set-up .......................................... 17
    2.2.3 DCM Set-up ............................................. 20
  2.3 Water Heater Test Bench ..................................... 21
    2.3.1 Flow Meter and Control Valve for Water Heater ........ 22
    2.3.2 Water Draw Schedule .................................... 23
  2.4 System Set up ............................................... 25

3 Results & Analysis 27
  3.1 DERMS, DCM, and DER Communication Network System .......... 27
  3.2 Grid-DER Service Dispatch ................................... 32
  3.3 DER CTA-2045 Conformance and Interoperability Testing ....... 35
  3.4 Grid-DER Services Testing .................................... 39

v
## List of Tables

1.1 Grid-DER services categories, purposes, and actions. ...................... 11

2.1 Water heater identifiers, capacity specifications, and set point temperatures. . 17

3.1 Hot Water Drawn Event for Test Bench ..................................... 39
3.2 WHs A and C ET and temperature and Energy (CPE) ........................ 49
3.3 WHs A and C ET and temperature in Energy (CPE) .......................... 53
3.4 Water Draw Event for DERMS grid-DER Service Testing .................... 60
List of Figures

1.1 Net Load Curve of Peak Energy Demand Period .......................... 2
1.2 Renewable Energy Generation of Solar and Wind from CAISO ............... 2
1.3 Classifications of DR programs ........................................... 9
1.4 Common DER grid services and alternative terminology ..................... 11
1.5 Common DER grid service response times and duration. .................... 12
1.6 EGoT overview: communication between DERMS, DCM and DER ............ 14

2.1 Heat Pump Water Heater Function ........................................ 18
2.2 Electric Water Heater Function ............................................ 19
2.3 EIA Average Electrical Load .............................................. 24
2.4 Grid-DER service system overview ........................................ 26

3.1 Sequence diagram of TLS handshake and communication messaging process . 28
3.2 Sequence Diagram of DERMS, DCM, and DER communication process .... 36
3.3 Sequence diagram of communication process between DCM - DER .......... 38
3.4 WH A EWH baseline operation result ..................................... 40
3.5 WH A HP baseline operation result ........................................ 41
3.6 WH B EWH baseline operation result ..................................... 43
3.7 WH C EWH baseline operation result ..................................... 44
3.8 WH A EWH Energy (Shed) Service Result ................................ 45
3.9 WH A HP Energy (Shed) Service Result .................................. 46
3.10 WH B EWH Energy (Shed) Service Result ................................ 47
3.11 WH C EWH Energy (Shed) Service Result ................................ 47
3.12 WH A EWH Energy (CPE) Service Result ................................ 50
3.13 WH A HP Energy (CPE) Service Result .................................. 51
3.14 WH B EWH Energy (CPE) Service Result ................................ 51
3.15 WH C EWH Energy (CPE) Service Result ................................ 52
3.16 WH A EWH Blackstart Service Result ................................... 54
3.17 WH A HP Blackstart Service Result ....................................... 54
3.18 WH B EWH Blackstart Service Result ................................... 55
3.19 WH C EWH Blackstart Service Result ................................... 55
3.20 WH B Remote EWH Baseline Service Result ................................ 57
3.21 WH B Remote EWH Energy (Shed) Service Result ......................... 57
3.22 WH B Remote EWH Energy (CPE) Service Result ......................... 58
3.23 WH B Remote EWH Blackstart Service Result ............................ 58
Glossary

CDTA  Central Distributed Trust Aggregator. 19

CTA-2045  ANSI/CTA-2045-A. v, 4, 6, 7, 14, 17, 20–22, 26, 29, 33, 35, 37, 38, 53

DCM  Distributed Control Module. v, 5, 7, 13–21, 26–29, 31–33, 35, 37, 38, 53, 62, 74, 75, 100, 101

DDNS  Dynamic Domain Name System. 18


DERMS  Distributed Energy Resources Management System. v, 2, 5, 13, 15–20, 26–29, 31–33, 35, 59–63, 75

DHW  domestic hot water. 24, 25

DLC  direct load control. i, ii, 3, 4, 9

DOE  Department of Energy. 24, 25

DR  demand response. i, ii, 3, 4, 6–9, 13, 15, 16, 25, 37, 59, 73, 74, 76

DTM  Distributed Trust Model. 19

EGoT  Energy Grid of Things. v, 13, 15–17, 20, 21, 27

EIA  U.S. Energy Information Administration. viii, 23, 24

EPRI  Electric Power Research Institute. 6

ESI  Energy Service Interface. 10

ET  EnergyTake. 41–46, 48–52, 55, 59, 61, 62

EWH  Electric Water Heater. 17

GO  Grid Operator. 13, 32, 33, 53

GRA  Graduate Research Assistant. 56, 59
GSP  Grid Service Provider. 13, 17, 29

HPWH  Heat Pump Water Heater. 17

HTTPS  Hypertext Transfer Protocol Secure. 18

IEEE 2030.5  IEEE 2030.5 Smart Energy Profile 2.0. 4, 5, 14, 20, 26–28, 32, 33

IEEE 802.11  IEEE 802.11 Wireless Local Area Networks. 21

IoT  Internet of Things. 13

LAN  Local Area Network. 22

ME  Modeling Environment. 13, 63, 68

OEM  original equipment manufacturer. 35, 36, 41–43, 59, 60, 98

PNW  Pacific Northwest. 23

PSU  Portland State University. 16, 17, 59, 60, 98

RPi  Raspberry Pi 4 Model B. 20, 21

SEP  Smart Energy Protocol. 1

SGD  smart grid device. 7

SGIP  Smart Grid Interoperability Panel. 6

SOA  Service-Oriented Architecture. ii, 4, 73, 75

SPC  Service-Provisioning Customer. 13

TB  Test Bench. 21–23, 26

TLS  Transport Layer Security. 19, 27–29, 33

VM  virtual machine. 17

WH  water heater. 3–5, 7, 8, 12, 16, 21, 22, 25, 26, 29, 31–33, 35–56, 58–63, 68, 75

XML  Extensible Markup Language. 20
1 Introduction

1.1 Problem Statement

Utility providers are faced with a challenge in integrating Distributed Energy Resource (DER) into customer homes, with the rapid advancements in smart household appliances and communication technologies. Simultaneously, factors of population growth, increased electric load adoption, and a surge in energy consumption are creating complexities in grid management. Figure 1.1 shows the electric power grid energy peak demand and its period, with the demand period located in late afternoon and evening [1]. Figure 1.2 shows renewable energy generation and its mismatch with peak demand: peak of generation occurs between 0800 to 1700 hours and the peak demand period occurs from 1800 to 2200 hours [2]. However, leveraging residential appliances as DERs emerge as an economically viable solution to alleviate grid-related challenges without requiring a comprehensive update of the existing electrical grid infrastructure. DERs, characterized as customer-owned assets for load, storage, or generation, possess the capacity to seamlessly interact with the power grid. Grid-interactive inverters, integral to enhancing grid reliability, offer utilities essential grid service functions like frequency-Watt and Volt-VAr curve control [3]. The effective management of energy consumption patterns is achievable through the application of the Smart Energy Protocol (SEP), also known as IEEE 2030.5 [4], serving as the communication
protocol for the Distributed Energy Resources Management System (DERMS). This problem statement underscores the need for innovative strategies to integrate DERs into the evolving energy landscape while ensuring grid reliability and efficiency.

Figure 1.1: Net Load Curve of Peak Energy Demand Period [1]

Figure 1.2: Renewable Energy Generation of Solar and Wind from CAISO [2]
Over the past decades, utility providers have worked to enhance the reliability of their services through the implementation of demand response (DR) programs. A notable example dates back to 1979 when the Florida Power Corporation pioneered a large-scale deployment of grid services using a direct load control (DLC)-based program for public customers [5]. This program, which continues to operate, aggregates various DERs such as water heaters (WHs), pool pumps, and central air-conditioners to curtail power consumption during peak times [6]. Despite its widespread adoption by utility companies, DR programs face a significant challenge, as customers participating in these programs lack control over their DERs once enrolled. The utility may cycle or switch off power to customers’ units without considering individual preferences. This lack of customer control, particularly in programs using air conditioners, has been linked to customer discomfort, leading to persistently low enrollment rates in direct load control (DLC)-based DR programs. This problem statement highlights the need for innovative approaches to programs that prioritize customer preferences and comfort, overcoming the present constraints of DLC strategies to achieve extensive customer involvement in DR programs and efficiently manage grid services for balancing power consumption during peak hours.

1.2 Objectives of Work

This thesis addresses the issues of high energy demand during peak demand period, satisfying customer’s comfort during grid-DER service, and deferring energy consumption. This work centers on using electric WHs as DERs, with a consumption range in low power
and energy and its natural behavior as a thermal energy storage device. Almost 40% of residential WHs in the United States are powered by electricity and account for up to 18% of residential electricity use [7]. The integration of intelligent energy protocols like ANSI/CTA-2045-A (CTA-2045) and IEEE 2030.5 Smart Energy Profile 2.0 (IEEE 2030.5) serves to facilitate information exchange between utility providers and these vital appliances, thereby augmenting the efficiency and responsiveness of grid management.

Within the scope of managing residential WH as DERs, Service-Oriented Architecture (SOA) is implemented as a strategy to ensure that these DERs can be efficiently and flexibly managed to contribute to grid stability, especially during peak demand times. By adopting SOA, the grid-DER service program aims to facilitate secure communication between grid operational needs and DERs. This approach allows for the dynamic adjustment of energy consumption by residential WHs in response to real-time grid conditions, ensuring not only the stability of the grid but also maintaining the comfort levels of participating customers. SOA, in this context, represents a shift towards more customer-centric and adaptable grid management practices, where DERs can be managed as a collective resource while addressing the potential issue of customer discomfort experienced in previous DR events in DLC programs.

The subsequent phase involves demonstrating various grid services through physical DERs, using the commodity command capabilities of CTA-2045. This exploration aims to ascertain the suitability of DER behaviors for Grid-DER services. This thesis then advances by comparing the real-time performance of WH units with simulated DER units within a
modeling environment.

In addressing concerns related to customer privacy and optimizing data exchange, the study employs a focused approach. Only four essential parameters – Duration, Interval, Power, and EnergyTake – are shared between the Distributed Control Module (DCM) as a client and the DERMS as a server. This limited data exchange is facilitated through the application of IEEE 2030.5 messaging [4, 8]. While this approach deliberately restricts the detailed asset information exchanged, it proves sufficient for utilities to deliver grid services effectively to participating DERs.

This work makes several foundational contributions that significantly advance the integration and operational of DERs within the grid energy management framework. Firstly, it achieves the integration of critical components within grid architecture, namely DERMS, DCM, and DERs, ensuring they function cohesively to respond to grid demands. This is further augmented by the practical implementation of grid-DER services within both DERMS and DCM, which establishes a direct link between theoretical concepts and their application in real-world scenarios. Additionally, the last part of the thesis introduces a modeling environment that synthesizes live DER data, offering to analyze physical DER behaviors in response to various grid-DER services. A practical testament to this integration is developing a test bench WH station equipped with a realistic water draw schedule to validate the hot water consumption in the work. These contributions underscore the role of this research in pushing the boundaries of how DERs can be effectively managed, aligning with the goals of enhancing grid stability and optimizing energy consumption while prioritizing
the comfort and satisfaction of the end users.

1.3 Literature Summary

1.3.1 CTA-2045 Communication

With the overarching goal of creating a universal DR standard for appliances, the CTA-2045 specification was developed around the early 2000s by the Electric Power Research Institute (EPRI) and the Smart Grid Interoperability Panel (SGIP) as a modular communication system [9]. This initiative aimed to establish a versatile standard applicable to a wide array of devices and manufacturers [10]. Beyond communication protocols, the standard also defines a socket interface, and ensures that devices are equipped with energy management functions right from the manufacturing stage to achieve both interoperability and user-friendly installation for the consumer.

By integrating various CTA-2045 functions into DERs during manufacturing, both manufacturers and consumers gain the ability to contribute in DR programs [11]. These initiatives support power utilities in managing peak-period power consumption, leading to reduced strain on the grid and lower electric bills for participants, which is a clear win-win scenario. However, the effectiveness of this approach relies heavily on customer participation. Thus, ensuring customer satisfaction and retention within the program becomes crucial.

Given that the CTA-2045 functions have been incorporated into DERs during the manufacturing process, it is helpful to explore the capabilities of these functions that are provided by the CTA-2045 standard. These are the basic DR messages in CTA-2045 communicated
from the DCM to the DER, which is referred to as a smart grid device (SGD) in the CTA-2045 standard.

- **End-Shed**: Upon concluding a curtailment event, the SGD resumes its standard operation.

- **Shed**: During a curtailment event, the DCM sends a message to the DER, instructing it to lower power usage while maintaining the customer’s comfort.

- **Critical Peak Event**: When this message is sent from DCM to SGD, the device will respond by significantly reducing the power consumption during the peak demand period.

- **Grid Emergency**: The grid emergency function activates emergency measures among connected devices to maintain grid stability and prevent outages during critical stress periods.

- **Load-up**: Opposite of Shed. Directs the SGD to consume energy immediately, if possible.

Conducting tests using the CTA-2045 standards with WHs, such as Shed, Endshed, Load-up, Critical Peak Event and Grid Emergency demonstrates the response of each function and the corresponding behavior of the water heater [11]. This analysis illustrates how these functions can significantly enhance an aggregator’s capacity for energy management, particularly in facilitating DR programs. By showcasing the versatility and effectiveness
of these services, it paves the way for a more resilient and efficient energy infrastructure capable of accommodating increased demand and fluctuations in consumption.

### 1.3.2 Demand Response

DR programs were established to address the challenges from fluctuations in electricity demand and grid instability [12]. These initiatives effectively manage energy consumption during peak periods, typically when demand is highest, by incentivizing consumers to adjust their usage patterns. By encouraging consumers to reduce or shift electricity usage during these times, DR programs assist utilities in maintaining grid reliability, preventing overloads, and avoiding costly infrastructure upgrades. Moreover, these programs aid in energy conservation efforts and facilitate the integration of renewable energy sources by aligning electricity supply and demand more efficiently. Figure 1.3 [12] illustrates all the programs classified under demand response.

Expanding on the significance of DR programs in ensuring grid stability and energy efficiency, the use of WHs in these schemes amplifies their efficacy and sustainability. Integrating WHs into DR programs as DERs offers benefits such as grid flexibility, load shifting, and energy efficiency [13, 14, 15]. Participation in these programs enables consumers to save through financial incentives, while contributing to environmental sustainability by reducing emissions [12]. By optimizing energy use and integrating renewable sources, electric water heaters support grid reliability and resilience, empowering consumers to actively engage in managing their energy consumption.
DR programs play a crucial role in enhancing grid stability by optimizing energy use and reducing peak demand. However, while strategies like direct load control (DLC) offer...
grid operators effective means to manage energy consumption, they may inadvertently lead to consumer discomfort and dissatisfaction [5]. This discomfort could result in consumers opting out of the program altogether, undermining effectiveness in achieving long-term grid reliability and sustainability goals. Therefore, in this thesis we investigate an alternative approach that prioritize both grid stability and consumer satisfaction.

### 1.3.3 Grid-Service Definition

The concept of developing grid service definitions originates from the operational framework designed to oversee the electric power system. The objective is to establish a shared set of definitions for grid services pertinent to interactions with DER, encompassing responsive generation, storage, and loads. Moreover, it aims to promote the idea and criteria of the Energy Service Interface (ESI) to the extent of initiating relevant interface standards and guidelines applicable to communication protocols [16]. The development of these grid services entails defining their purpose, terms, and classifications to address various operational objectives typically encountered in power system operations. Figure 1.4 [16] shows the common types of Grid-DER services and their alternative terminologies.

Each grid service is accompanied by specific performance expectations, outlining the behaviors necessary from resources to render the service meaningful. These expectations are defined by a unique blend of service attributes, which dictate the requisite actions for effective service provision. Performance metrics are tailored for each grid service, based on the most relevant service attributes. These metrics play a vital role in the resource validation processes [16]. Table 1.1 shows the six grid-DER services, their purpose, and actions.
Table 1.1: Grid-DER service name, purpose, and action table with definitions and applications

<table>
<thead>
<tr>
<th>Grid Service</th>
<th>Purpose</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Ensure adequate energy resource supply</td>
<td>Consume/produce a specified amount of energy over a scheduled period</td>
</tr>
<tr>
<td>Reserve</td>
<td>Reserve source or load capacity</td>
<td>Adjust real power for dispatched in a contingency</td>
</tr>
<tr>
<td>Regulation</td>
<td>Support area control error</td>
<td>Adjust real power following an automatic control signal</td>
</tr>
<tr>
<td>Blackstart</td>
<td>Support recovery of a collapsed power system</td>
<td>Sources supply power and support voltage. Loads defer post-recovery consumption</td>
</tr>
<tr>
<td>Voltage Management</td>
<td>Detect and correct voltage excursions</td>
<td>Control reactive and/or real power of sources and loads</td>
</tr>
<tr>
<td>Frequency Response</td>
<td>Detect and arrest sudden frequency deviations</td>
<td>Control real and/or reactive power of sources and load</td>
</tr>
</tbody>
</table>

Grid service timing attributes encompass parameters dictating service delivery timing and speed. The delivery schedule defines when the service occurs, detailing start and end times or calculated duration. Figure 1.5 shows the response and duration of each grid-DER service. For on-call services like reserves, it reflects resource availability. Delivery schedule notification informs participants of service delivery schedules, typically via market process.
results. Response time measures the interval from scheduled start to desired behavior meeting thresholds, varying from milliseconds to hours per service agreement. Some services demand near-instantaneous responses, necessitating autonomous behaviors like Volt/Watt and Frequency/Watt curves.

Figure 1.5: Grid-DER response time, duration of service with service types and time frame of duration and response time [16]

Figure 1.5 illustrates the response time, duration of service and the service types. Such that each color in the graph it is represented by the service type, and how the response time and duration of service would be like in an event. For example, the Energy service response time needs to be short such that it needs to be in the minutes. But its duration for the service can be long, such that consumer can schedule this service daily to contribute the power grid to reduce energy during peak demand period. However some other services needs to be in a short response time and duration such as Frequency Response.

In this thesis, we focus on using WHs as DERs, specifically for Energy and Blackstart grid services. Section 2 delves deeper into these grid-DER services, providing comprehen-
sive insights. Section 3 showcases the outcomes of activating these grid-DER services within physical residential DERs. This work uses real-time data from these DERs and integrates them into a Modeling Environment (ME), facilitating a comparison between physical and simulated DERs.

1.4 Energy Grid of Things

The Energy Grid of Things (EGoT) represents an innovative approach like the Internet of Things (IoT) into conventional energy grid networks [17, 18]. This integration facilitates more intelligent control and surveillance of the processes involved in distributing, consuming, and generating energy. Using real-time data and automated systems, Energy Grid of Things (EGoT) boosts the efficiency, dependability, and eco-friendliness of the energy sector, leading to a more reliable and more flexible grid.

In this thesis, the EGoT is described as comprising three principal systems that interact to enhance the management of grid-DER services, particularly for DR programs. These components are: Distributed Energy Resources (DERs), a Distributed Energy Resources Management System (DERMS), and Distributed Control Modules (DCMs). Section 2 discusses each of these components in greater detail, elucidating their roles and interactions within the EGoT framework.

Figure 1.6 provides a simplified overview of the EGoT system. It illustrates how the Grid Operator (GO) interacts with the Grid Service Provider (GSP), which, in turn, employs DERMS messaging to communicate with Service-Provisioning Customers (SPCs) through
Figure 1.6: EGoT overview with all actors and communication between DERMS, DCM and DER

the IEEE 2030.5 standard [4]. Within the domain of each customer, the DCM and DER
engage in communication through the CTA-2045 standard for the provision of grid services.
2 Design Methodology

This section contains the discussion of the work objective, providing a comprehensive examination of each system component and its significance. Additionally, the work explores the parameters for testing and detail the methodology employed in conducting our experimental analysis.

2.1 Objective

The primary objective of this thesis is to modify and field-test an EGoT system integrated with physical DERs to provide grid services. This study aims to evaluate the performance of these systems within DR programs to ascertain if they operate as expected. Following this, the work used a grid simulator to create a modeling environment, using live data from the physical DERs during grid service activities. This facilitate an in-depth analysis of the behavior of a diverse array of DERs on a large scale during grid service operations.

2.2 Energy Grid of Things Configuration

The EGoT system is an intricately designed Service-Oriented system, comprising three components: DERs, DCMs, and a DERMS. The following subsections provides a compre-
hensive exploration of each component, clarifying their operational mechanisms and the roles they play within the EGoT framework.

This detailed examination not only highlights the individual functionalities of DERs, DCMs, and the DERMS but also illustrates how they work together to create an efficient system. Through this thesis, we aim to provide a clear understanding of the EGoT system architecture and its contribution to optimizing energy management processes.

### 2.2.1 DER Set-up

Within the scope of grid services, DER manifest in myriad forms. However, for the purposes of this thesis, our focus narrows to specific DER types: resistive water heaters and heat pump water heaters, sourced from three distinct manufacturers. This selection enables a detailed exploration of their operational dynamics and contributions to the broader energy system, providing valuable insights into their performance and utility in real-world DR program applications. Through this concentrated examination, we aim to shed light on the nuanced roles these DERs play in enhancing grid efficiency and sustainability.

To maintain confidentiality, this work refer to the manufacturers of the water heaters under examination as manufacturer A, B, and C. Each WH is calibrated with a temperature set point of 130 °F. Located within the Portland State University (PSU) Power Laboratory, test units have a nominal\(^1\) capacity of 50 gallons each, with the exception of a off-campus WH unit that has a smaller nominal capacity of 40 gallons, shown in Table 2.1. Furthermore, these WHs are designed with the capability to integrate with DCMs, facilitating the

\(^{1}\)Often, actual WH capacity is four or five gallons less than the nameplate capacity.
assessment of compatibility and interoperability between DCM and DER. This testing uses the CTA-2045 standard to conduct assessments of DERs performance within the energy management system.

Table 2.1: Water heater identifiers, capacity specifications, and set point temperatures.

<table>
<thead>
<tr>
<th>Water Heaters</th>
<th>Volume</th>
<th>Set Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH-A-EWH</td>
<td>50 Gal</td>
<td>130°F</td>
</tr>
<tr>
<td>WH-A-HP</td>
<td>50 Gal</td>
<td>130°F</td>
</tr>
<tr>
<td>WH-B-EWH</td>
<td>50 Gal</td>
<td>130°F</td>
</tr>
<tr>
<td>WH-B-EWH-REMOTE</td>
<td>40 Gal</td>
<td>130°F</td>
</tr>
<tr>
<td>WH-C-EWH</td>
<td>50 Gal</td>
<td>130°F</td>
</tr>
</tbody>
</table>

Figures 2.1 and 2.2 illustrate the functionalities of Electric Water Heater (EWH) and Heat Pump Water Heater (HPWH) [19, 20]. Figure 2.2 shows the EWH components such as the upper and lower heating elements and the cold water inlet, which refills water at the bottom of the tank as hot water leaves at the top of the tank. Figure 2.1 shows that HPWH has different component than the EWH, such as the HPWH main electric heating element as well as the compressor, which both heat the water to the set temperature point.

2.2.2 DERMS Set-up

Within the framework of the EGoT system, the DERMS functions as an aggregation system tasked with managing DCMs from the utility perspective, particularly on the GSP side. In this work, the DERMS is represented by a server located within the server computer of the PSU Power Engineering Laboratory.

This server is configured to operate on a virtual machine (VM), using an UNRAID server architecture to ensure seamless performance and scalability. Additionally, to bolster
system information security, we used Dynamic Domain Name System (DDNS) in tandem with the Hypertext Transfer Protocol Secure (HTTPS) protocol. This combination not only guarantees the integrity and confidentiality of data transactions, but also underscores our commitment to maintaining a secure communication network system.

Before any communication occurs between DERMS and DCM using the IEEE 2030.5 standard [4], a thorough authentication process is necessary to ensure secure and trusted exchanges. In this preliminary stage, both the client (DCMs) and the server (DERMS) are equipped with unique, encrypted keys and certificates to establish a foundation of trust. Specifically, the server retains a copy of the client’s certificate and key, whereas the client holds the server’s certificate. This mutual authentication serves as the cornerstone for a
secure connection, culminating in a Transport Layer Security (TLS) handshake. This step signifies the server is prepared to engage in secure and efficient communication, ensuring that all interactions between DERMS and DCMs are safeguarded from inception.

During communication between the DERMS and DCMs, it is important to maintain robust security measures to shield both entities from potential cyber threats. To this end, the Central Distributed Trust Aggregator (CDTA) and the Distributed Trust Model (DTM) frameworks were developed, offering a solid defense against cyber-attacks [21, 22].
exchanges between the DERMS and DCMs are formatted in Extensible Markup Language (XML) to strike a balance between readability and security. Moreover, with a strong emphasis on customer privacy, the content of these messages is deliberately kept concise. This approach focuses on transmitting only four essential flow reservation parameter values: \textit{EnergyTake}, \textit{Power}, \textit{Duration}, and \textit{Interval}. Such minimalism not only enhances privacy protection for customers but also streamlines the communication process, ensuring that only necessary information is shared, thus bolstering the overall security posture of the communication channel.

2.2.3 DCM Set-up

The primary function of the DCM is to serve as a gateway, facilitating seamless interaction between DERMS and DER within the EGoT system. This communication bridge uses the CTA-2045 protocol for DCM to DER messaging, and the IEEE 2030.5 standard for messaging between the DCMs and DERMS, ensuring a harmonized and secure communication flow.

The DCM architecture is built around three fundamental components:

- **Raspberry Pi 4 Model B (RPi) (Computation)**: This device offers the necessary processing capabilities to manage and coordinate communications efficiently.

- **RS-485 CAN HAT** (Serial Communication): This module enhances the Raspberry Pi by adding robust serial communication capabilities for interacting with DER.
- **Uninterrupted Power Supply Board and Battery Pack** (Power and Backup): Ensuring the DCM remains operational even in the event of power disruptions, this component provides a reliable power backup solution.

  Given that the WH DER typically supply 120 V AC power via the EcoPort connection, and the RPi operates on 5 V DC, a power converter is used to adapt the 120 V AC into a suitable 5 V DC input for the RPi. Additionally, a 10 Ah battery pack stands ready to supply power to the RPi should there be any interruption in the AC power from the DER, ensuring continuous operation [23].

  Once the RPi is powered appropriately through the converter, it adheres to the IEEE 802.11 Wireless Local Area Networks (IEEE 802.11) WiFi standards, forming the foundation for wireless communication [24]. Following this, the RS-485 CAN HAT module is integrated with the RPi, marking the completion of the DCM assembly and signaling its readiness to bridge communications within the EGoT system efficiently.

### 2.3 Water Heater Test Bench

In this work, four 50-gallon WHs are controlled and monitored using the WH Test Bench (TB). This system is powered by RPis, a compact, single-board computer [25]. The TB engages in communication with the WH through CTA-2045 standards for grid-DER services by executing commodity commands. It also enables the system to gather and relay information from the WHs, offering a comprehensive overview of their operational status [26].
Additionally, it has connectivity to the laboratory Local Area Network (LAN) via Wi-Fi, highlighting its integrated design and ease of access for monitoring and control purposes.

Data acquisition is another critical function of the TB. It measures, records, and standardizes data from the WHs according to the CTA-2045 standard, ensuring data integrity and facilitating analysis. The system capability to emulated water usage through automated water draw schedules adds another layer of functionality, enabling realistic testing scenarios that mimic typical household water consumption patterns.

### 2.3.1 Flow Meter and Control Valve for Water Heater

To facilitate precise and automated water usage simulations, each WH testing bay is outfitted with an electric ball valve connected to the WH outlet. This setup allows for controlled water release, driven by the 3.3 V GPIO output that activates a solid-state relay. This relay, in turn, powers the valve with a 120 V supply.

This setup extends to water usage monitoring, using the Omega FPR303 flow meter. As water flows through this device, it propels a specially designed impeller. This impeller incorporates a magnet within one of its blades, passing by a Hall effect sensor with each rotation to generate a voltage pulse. These pulses are instrumental in measuring water flow, with the meter precision highlighted by the specific rotations per gallon metric, uniquely calibrated for each unit and noted on its housing.

During water draw events, a Python program calculates the total water flow by counting the rising edges of the flow meter pulses allowing for accurate water usage data collection.
The flow meter integration is further refined by its dedicated 24 V power supply, ensuring its operational integrity. To harmonize with the TB 3.3 V logic, the flow meter output is carefully divided down to 3 V, preventing any potential damage from over-voltage to the GPIO pin. Additionally, the incorporation of a pull-up resistor at the GPIO pin accommodates the flow meter current sinking sensor, rounding off a highly effective system designed for both precision and reliability in water usage simulation and data collection.

2.3.2 Water Draw Schedule

To optimize our laboratory test bench for water draw, using valve and flow meter control, it is important to first establish a water draw schedule that accurately mirrors the patterns of user water consumption events. This necessitates an understanding of the daily peak demand periods as observed on the utility side. Insights from the U.S. Energy Information Administration’s study reveal notable seasonal variations in these peak periods in electric load within the Pacific Northwest (PNW) [27]. During the spring and fall, the demand curve remains relatively flat, indicating a lower variation in power usage throughout the day. In contrast, the winter season presents dual peak periods in the morning and late afternoon, whereas the summer season experiences its singular, most pronounced peak in the late afternoon shown in Figure 2.3 [27]. This seasonal behavior underscores the importance of tailoring our water draw schedule to reflect these fluctuations, ensuring our testing conditions are as realistic as possible.

Given that the highest peak demand period predominantly occurs in the summer season, typically in the late afternoon, we crafted a water draw profile that accurately simulates
Figure 2.3: U.S. Energy Information Administration average hourly load in daily electricity behavior by regions and selected months [27].

this peak demand time frame. This enhances our ability to replicate real-world water usage patterns effectively within our simulations. The basis for our water draw event profile is the Department of Energy (DOE)’s domestic hot water (DHW) event schedule [28]. We set the simulation parameters to reflect a household in Portland, Oregon, with a three-bedroom configuration, and analyzed water usage data spanning the winter (December 19th to March 19th) and summer (June 20th to September 22nd) periods.

The analysis pinpointed the most significant water draw event occurring on July 25th, marking the peak of our observation period. This event saw the highest water usage, reaching 36 gallons between 6:00 PM and 7:00 PM. This insight is important for developing a water draw schedule that mirrors the peak demand periods, ensuring our laboratory simulations
align closely with actual user behavior and utility patterns. To effectively simulate a water draw event within the context of peak hours, our model delineates the peak period to span three hours, from 6pm to 9pm. This timing was chosen to mirror the typical increase in water usage observed in standard households post-work hours during the summer months. Our analysis leverages peak water consumption data sourced from the DOE’s DHW event schedule, specifically focusing on data from July 25th, between 18:00 and 21:00. Given the limitations of our water heater testing station, which cannot process water draws exceeding roughly 20 gallons at a time to prevent overflow in the sink, we structured the schedule into 15-minute intervals. Each interval represents a distinct quantity of water being drawn, thereby allowing us to closely monitor and analyze consumption patterns within the designated peak period.

2.4 System Set up

Upon the successful assembly and setup of all systems, we initiate field testing of all four WHs. These tests focus on evaluating WH compatibility and interoperability with various grid-DER services. The primary objective is to analyze their behavior and outcomes in the context of DR program challenges, thereby assessing their potential contribution to effective energy management.

To facilitate this analysis, development of water draw schedule profile was conducted such that it draws from peak hour hot water event data provided by the DOE. This enables precise control over water draws using a valve control mechanism integrated with our water
heater test bench station. In addition to the water draw events, we will incorporate a DCM within the WH system, employing the CTA-2045 standard for seamless communication. Furthermore, the communication link between the DCM and the DERMS use the IEEE 2030.5 standard, ensuring a robust and efficient exchange of information. Figure 2.4 demonstrates how the system operates with WH testing station, DERMS, DCMs and DERs. The WH valve control, flow meter and current transformer (CT) are connect to the TB raspberry pi via GPIO pins. The purpose of the TB is to control WH water draw event and volume by its profile. The DCM communicates with the DER via CTA-2045 standard and the DCM device is mounted on the WH. The DERMS communicates with DCM with IEEE 2030.5 standards and the communication is through wireless client and server network.

Figure 2.4: Grid-DER service system overview with water heater test bench, DCMs and DERMS.
3 Results & Analysis

3.1 DERMS, DCM, and DER Communication Network System

The EGOT system marks a significant advancement in grid energy management, with the DERMS at its core overseeing energy use across various DERs like distributed generators, flexible loads, and energy storage. This system provides energy management to meet demand efficiently.

A important aspect of this setup is the secure communication between DCMs and the DERMS, established through a TLS handshake to protect data integrity, such that the DERMS and DCM will exchanges certificate for the authentication of the entity. Then the DERMS server and the DCM conducted a verification on the certificate, once authentication it is established the communication network between DERMS and DCM it is secured and ready for communications use.

Following the TLS handshake, the DERMS initiates a request for the flow reservation parameters from the DCM. Once DCM received the request from DERMS then the DCM will response specified flow reservation parameters through IEEE 2030.5: EnergyTake, Power, Duration, and Interval. The rationale behind these four parameters in communications is to optimizing the volume of data transmitted, thereby enhancing the safeguarding of consumer privacy and to ensure the utility is provisioned with critical data for the grid-DER services.
Figure 3.1 illustrates the TLS hand shake process as well as the flow reservation parameter values message exchange through IEEE 2030.5, then DCM requested service when the service is posted and DERMS response to the DCM with the service type and duration for the grid-DER service.

Example Messages 3.1 illustrates how a flow reservation requests from five DCMs are
formulated and then processed by the DERMS on the GSP) side. Such that each message will sent from individual DCM that is attached to the WH physically and gathered the flow reservation parameter messages through CTA-2045, then each DCM will send their message to the DERMS after the TLS handshake. This interaction is key to making informed decisions on energy distribution and highlights the importance of secure, efficient communication in managing a sustainable and reliable electric grid. Through this process, the DERMS aligns energy supply with demand, optimizing grid performance and contributing to a more efficient energy ecosystem.

Receive message 3.1: DERMS receives flow reservation request from DCMs:

DCM_1_Messages_to_DERMS
Received Order ID: 78913
Received Customer: WH_A_EWH
Received Interval: 3600.0
Received Duration: 3.16
Received Power: 4500.0
Received EnergyTake: 1425.0
Received Timestamp: 2024-03-12 15:09:38

DCM_2_Messages_to_DERMS
Received Order ID: 78913
Received Customer: WH_A_HP
Received Interval: 3600.0
Received Duration: 0.96
Received Power: 800.0
Received EnergyTake: 825.0
Received Timestamp: 2024-03-12 15:09:40

DCM_3_Messages_to_DERMS
Received Order ID: 78913
Received Customer: WH_B_EWH
Received Interval: 3600.0
Received Duration: 0.79
Received Power: 4500.0
Received EnergyTake: 5697.0
Received Timestamp: 2024-03-12 15:09:44

DCM_REMOTE_Messages_to_DERMS
Received Order ID: 78913
Received Customer: WH_B_EWH_REMOTE
Received Interval: 3600.0
Received Duration: 0.94
As Messages 3.1 illustrates above, the DERMS receives information from each of the five DCMs that contains the *Flow Reservation Parameter* messages as well as the made up *Order ID* with each of the DER named *Customer* that the DCM is attached on. In this example, the WH C *Power* and *Duration* values are zero because this unit it is not participating in the service at that time, whereas the remaining four WHs are participating in the service and their flow reservation parameter values are non-zero. These messages are sent out by the DCMs every 30 seconds for the DERMS to conduct grid-DER service in the future as needed.
3.2 Grid-DER Service Dispatch

This section discusses the dispatch process of grid-DER services, initiating from the GO selection of service type and duration. The catalog of service types under selection of Energy (with subsets Shed and Critical Peak Event) and Blackstart functionalities, for resistive and heat pump WHs. The implementation duration is articulated on an hourly basis, enabling the GO to adjust the grid-DER service duration in alignment with the electrical grid’s need.

In the preceding the actual dispatch of grid-DER services, the GO selects service types and duration to the DERMS. This briefing includes information such as the intended service duration and the categorization of service types (Energy(Shed, Critical Peak Event), and Blackstart). These services are designed to either attenuate energy consumption during peak demand windows or to earmark energy reserves for critical infrastructure in exigent scenarios. Under Baseline operation, the focus pivots to the surveillance of the normative operation of the DER units. Code A serves as an exemplar, showing the service type and duration selection interface available to the GO for creating a grid-DER service engagement, with a specific illustration featuring a baseline service with a 3.5-hour duration intended for the standard operational monitoring of DERs.

Subsequent to the GO’s selection of the service type and duration, the DERMS is tasked to send this information to the DCM via the IEEE 2030.5 protocol. Code B shows the DERMS received the current flow reservation parameter data for a specific WH and DCM (WH B), culminating in the DERMS issuance of a baseline operation directive to its DCM.
for initiating a 3.5-hour monitoring window for WH B. Code C reveals the WH B DCM receipt of service type and duration information from the DERMS, positioning it for the activation of grid-DER service.

Figure 3.2 maps the interactions among the DERMS, DCM, and DER units in facilitating grid-DER service execution. Within this schematic, the red vertical bar symbolizes the service duration time frame. Prior to service initiation, a sequence of communications between the DERMS and DCM via IEEE 2030.5 following the completion of a TLS handshake, the DCM engages the DER units through CTA-2045 protocol, executing commodity request and response cycles. Upon receiving the service type and duration parameters from the GO, the DERMS relays this information to the DCM, which in turn communicates back to the DERMS with flow reservation parameter values. The DCM then issues a Load-Up command to the WH for acknowledgment, catalyzing a preparatory heating phase of 30 minutes for the WH, during off-peak demand periods and prior to the service command. Following the Load-Up phase, the DCM dispatches the service command to the DER, which the DER will acknowledges and responds accordingly. Throughout the service engagement, the DCM furnishes the DERMS with real-time updates regarding the WH’s flow reservation parameter metrics.
Code A: GO Applies Service Duration & Type Information:

Choose a service:

1. baseline
2. energy-s
3. energy-c
4. blackstart

Enter the number corresponding to your chosen service: 1

You have selected 'baseline' service.

Enter the duration of the service in hours: 3.5

Code B: DERMS Sending out DCM Service Type and Duration

Server started on http://127.0.0.1:8080
127.0.0.1 - - [21/Mar/2024 15:59:22] "POST / HTTP/1.0" 201 -

Received Order ID: 78913
Received Customer: WH_B_EWH
Received Interval: 3600.0
Received Duration: 0.0
Received Power: 0.0
Received EnergyTake: 3418.0
3.3 DER ANSI/CTA-2045-A Conformance and Interoperability Testing

During the field testing of the Energy and Blackstart grid-DER services, a detailed evaluation was carried out. This involved the activation of a Loadup command on WHs from three different original equipment manufacturers (OEMs) [29, 30]. This approach provided a
unique opportunity to closely examine and compare the performance of these WHs under specific operational scenarios. The analysis of data collected, which included metrics such as EnergyTake and Real Power values, revealed differences between the three OEMs. These differences offer a deeper understanding of how varied WH units react to grid service management directives, providing insights for the future operation of systems and enhancing...
our comprehension of flexible load behaviors in DR situations.

The WH units from Manufacturer A, B, and C exhibit notable differences in their compliance and response behaviors according to the CTA-2045 protocol. The Manufacturer A unit requires the use of the Outside Communication Connection Status command to align with the protocol and ensure compliance. This unit demonstrates distinct responses to both Shed and Critical Peak Event commands, a feature desirable to utilities that prefer engaging more frequently with the Shed mode for grid services rather than the Critical Peak Event mode. However, a concern arises when the unit receives a Load Up command; it erroneously records an Op State Code for "Idle Heightened" in the logged data, potentially affecting utilities’ perception and interpretation of this operative mode.

Conversely, the Manufacturer B and C water heater units operate without the need for the Outside Communication Connection Status command. This approach technically renders the unit non-compliant with the CTA-2045 protocol. Additionally, the unit response to both Shed and Critical Peak Event commands is identical, diverging from the expected distinct behaviors. Although this identical response might be acceptable in certain scenarios, it may not meet the utilities’ preference for a more nuanced engagement with the Shed mode for grid services, as opposed to the Critical Peak Event mode. This comparison underscores the importance of adherence to protocol specifications and the potential implications of operational discrepancies on utility operations and protocol compliance.

Figure 3.3 illustrates the messaging between the DCM and the DER, specifically a WH, following the CTA-2045 standard, presented in a sequence diagram. When communicate
from DCM to DER an *Outside Communication* command must sent out from DCM to DER no longer than 15 minutes to satisfy CTA-2045 protocol, fail to send out this command will result the WH go back to normal operation, which it may not be useful if it occurs in grid-DER service. Once *Outside Communication* is sent to DER from DCM, then DER will send DCM acknowledgment of message is received, then DCM and DER will exchanges commodity request / response. Shortly after the exchanges, in this work it was programmed to be 10 seconds, then DCM can send out the command to the DER (In this example we are using *End-Shed*) and every 10 minutes it will repeats the process of sending out *Outside Communication*. 

Figure 3.3: Sequence Diagram shows communication process between DCM and DER in Energy service using Shed command, where "Outside-Communication" needs to be send before service command in every 10 minutes for the duration of the service.
Communication before sending out other commands.

3.4 Grid-DER Services Testing

In this section it discusses the purpose and the testing parameter of the grid-DER services as well as the baseline operation for all five of the WHs. In this testing, there are three grid-DER services Energy (Shed, Critical Peak Event), Blackstart. The Energy service is aim to reduce energy consumption during peak demand period while maintaining consumer’s comfort, the Shed it is a lighter energy reduction than Critical Peak Event. The Blackstart service is aim to eliminate the power consumption of the DER while under an emergency event.

Before initiating the grid-DER service, the test bench has a water draw event profile to simulate consumer water usage during peak demand periods, as outlined in the Section 2. Typically, these peak periods last between 2 to 4 hours, occurring in the late afternoon during summer and both in the morning and late afternoon in winter. For this field testing, we focus on replicating the most extreme water usage scenario observed in the summer. Specifically, the event recorded on July 25th, as documented in the DOE DHW events [28]. A schedule of this event is presented in Table 3.1, providing an emulation of consumer behavior during peak demand.

<table>
<thead>
<tr>
<th>Hour (hhmm)</th>
<th>1815</th>
<th>1830</th>
<th>1845</th>
<th>1900</th>
<th>1915</th>
<th>1930</th>
<th>1945</th>
<th>2000</th>
<th>2015</th>
<th>2030</th>
<th>2045</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Water Drawn (Gal)</td>
<td>3.85</td>
<td>20.74</td>
<td>14.53</td>
<td>0.72</td>
<td>0.8</td>
<td>3.36</td>
<td>1.2</td>
<td>2.13</td>
<td>2.09</td>
<td>2.1</td>
<td>1.87</td>
<td>1.79</td>
</tr>
</tbody>
</table>

Table 3.1: Hot Water Drawn Event for Test Bench
3.4.1 Baseline Operation

The *Baseline* operation aim to monitor the DER behavior during normal operation. In the following figures, the red line indicates the *Power* value which is in the unit of Watts (W), the blue line indicates the *EnergyTake* values which is in the unit of Watt-Hour (WHr), meaning the amount of energy the WH needs to heat the water to a certain temperature point. The green line indicates the water drawn amount which is in the unit of gallon (Gal). The left Y-axis are going from 0 - 4600 WHr (Electric Water Heater) and 0 - 5500 WHr (Heat Pump Water Heater) shows *Power* and *EnergyTake* and the right Y-axis goes from 0 - 22 in gallons and it shows the water drawn amount. The X-axis it is in 24 hours format such as hh:mm. The bottom three graphs are the state of operations such that starting from the top which is the *Load-up* period, *Service* period, and *End of Service* period, when the output is 1 meaning the state of that period it is activated, and 0 it is deactivated.

![WH_A EWH baseline operation result](image)

Figure 3.4: WH A EWH baseline operation result
In Figure 3.4, it shows the Baseline operation of electric WH A behavior during a peak period water drawn event. During its Load-up period, the unit heat up for a short period of time to the set temperature of the WH by activating its power and reducing the EnergyTake (ET) value, once it reaches the set temperature, the power then deactivated and the ET decrease to zero. During this Baseline operation this WH unit behave as expected because every time the water drawn event occurred the ET value also increased then the power was activated to heat up the WH to the set temperature and bring the ET value to zero.

![Figure 3.5: WH A HP baseline operation result](image)

In Figure 3.28, it shows the Baseline operation of heat pump WH from OEM A behavior during a peak period water drawn event. During its Load-up period, the unit heat up for a short period of time to the set temperature of the WH by activating its power and reducing the ET value, once it reaches the set temperature, the power then decrease from 5300 to
800 in Watt-Hour (WHr) which it activates the condenser and then it will decrease the ET. During this *Baseline* operation this WH unit behave as expected because every time the water drawn event occurred the ET value also increased then the power was activated to 5300 which is both the electric and the condenser of the WH to heat up to the set temperature and bring the ET value down.

In summary, each WH has different behaviors regarding to their ET responses to water draw events, and the power activation to decrease the ET. However, for WH in Manufacture B is not in conformance, because there is an error in the ET values calculation due to using weighted values from Equation 3.1 to calculate the tank temperature by only reading the lower part of the tank, such that it will make the upper temperature sensor part of the weighted value to be zero. Even when the upper part of the heating element is activated, upper temperature sensor can not read the temperature value because it is only reading the lower temperature value.

In Figure 3.6, it showcase the *Baseline* operation of the electric WH from OEM B behavior during a peak period water drawn event. For this unit, its behavior was different than the other WHs. When the water draw event started, the ET value increases and power was activated but it doesn’t reduce the ET value until around 1945 hour on the X-axis. In which at that time the split of a power value occurs. Then, the ET value will correspond to the water draw event, and also decreasing its value while the power is activated until ET reaches to zero. However, during the last two water draw, the ET was increasing but it never decrease down. This behavior is cause by the OEM’s design on miss calculating the ET
value. In Equations 3.1 it showcases how the WH tank temperature is calculated. A and B are weighted values from the two temperature sensors from the upper and lower elements of the WH.

In Equation 3.2, $T_{\text{tank}}$ is used to calculate ET, where 0.2930 Wh/lbF is the specific heat of water, $V_{\text{tank}}$ is the tank volume in gallons, and 8.249 is the density in pounds per gallon of water at 120$^\circ$F. The density of air-free water, $\rho$, is a function of temperature, which can be calculated using Equation 3.3. Temperature units are in $^\circ$F, except in Equation 3.3 where $^\circ$C must be used.

This WH from OEM B ET has unusual behavior. That behavior is caused by OEM uses weighted values $A = 1$ and $B = 0$ to be the weighted values, resulting that only the lower temperature sensor is being capture while calculating the ET value.

$$T_{\text{tank}} = AT_{\text{lower}} + BT_{\text{upper}} \quad ^\circ F$$  \hspace{1cm} (3.1)
Energy Take = (0.2930)(V_{tank})(8.249)(T_{set} - T_{tank}) \quad Wh \quad (3.2)

\[
\rho = (999.85308 + 6.32693 \times 10^{-2}T_{oC}^2 - 8.523829 \times 10^{-3}T_{oC}^2
+ 6.943248 \times 10^{-5}T_{oC}^3 - 3.821216 \times 10^{-7}T_{oC}^4) \quad kg/m^3 \quad (3.3)
\]

Figure 3.7 shows the Baseline operation of electric WHC behavior during a peak period water drawn event. During its Load-up period, the unit heats up for a short period of time to the set temperature of the WH by activating its power and reducing the ET value. However the ET value never reaches zero but instead stays around 50 WHr for this WH. Once it reaches the set temperature, the power then deactivates and the ET decreases down to around 50 WHr before increasing after a water draw event occurs. During Baseline operation this WH unit behaves as expected because every time the water draw event occurs, the ET value also increases then the power is activated to heat up the WH to the set temperature.
3.4.2 Energy (Shed) Grid-DER Service

This section examines the performance outcomes of WHs during their operation within the Energy service in Shed mode. The primary objective of the Energy service is to mitigate energy consumption during peak demand periods on the electrical power grid. As a scheduled service, Shed mode is designed to implement energy reduction strategies during the service duration, thereby achieving energy savings while simultaneously maintaining the comfort levels of customers.

![Graph 1](image1.png)
![Graph 2](image2.png)

**Figure 3.8: WH A EWH Energy (Shed) Service Result**

In Figures 3.8 (Electric) and 3.9 (Heat Pump), it demonstrates manufacture A WHs behavior during grid-DER Energy service in Shed mode. During its Load-up period, both WH units activate their power to heat up the tank temperature to its set point and reduce the ET to zero. During the service period and the water draw events, the ET of both WHs
respond to the initial two small water draw events by increasing the ET value but not activating their power. Once the ET value reaches its upper threshold, meaning that the tank temperature it is at the lower threshold, then power will be activated to heat the WH to the upper temperature threshold and reduce the ET value to its lower threshold. By having upper and lower temperature threshold during this service, utilities can reduce energy consumption and also shift the peak period.

In Figure 3.10 it showcase the Manufacture B electric WH behavior during Energy service in Shed mode. During its Load-up period, the WH did not activates its power because the ET values was zero, in which this is a normal behavior. However, when the power is activated during small water draw in the beginning of the service period, this behavior it is not expected. Finally, At the end of the service the power is activated but the ET value is not decreasing, this behavior is also not expected, thus it marks this unit out of
Figure 3.10: WH B EWH Energy (Shed) Service Result

conformance.

Figure 3.11: WH C EWH Energy (Shed) Service Result

Figure 3.11 shows cases the Manufacture C electric WH behavior during Energy service in Shed mode. This WH behavior is similar to electric WH A, where it only activates it power when a large amount of water draw event occurs, but with more power activation
In this Energy service of Shed mode, three out of four WHs are behaving as expected with the exception of WH from Manufacture B which it has unexpected behavior.

During this service, since three WHs from Manufactures A and C behavior are expected, and the ET value was increased and decreased to an upper and lower threshold in associate with the temperature, the upper and lower ET value was captured during the service period, especially in the time frame between 1900 to 2100 where the smaller volume of water draw events was occurring at that time and the ET values were fluctuating between lower and upper threshold. By using ET values calculated by the WH, we can create a new equation to find the estimate tank temperature. The equation that used by calculating ET value is Equation 3.2, by moving the $T_{tank}$ to the left side of the equation, as result we have Equation 3.4 to find the estimated tank temperature. Since Manufacture B WH is out of conformance due to the inaccurate reading on the ET value, the calculation of upper and lower temperature and ET threshold values will not include WH B. Table 3.2 shows WHs from Manufacture A and C with the results from the calculation of upper and lower threshold value of ET and temperature values.

$$T_{tank} = T_{set} - \frac{0.4137 \cdot Energy Take}{V_{tank}}$$

(3.4)
<table>
<thead>
<tr>
<th>Water Heater (OEM)</th>
<th>Lower ET (WHR)</th>
<th>Upper ET (WHR)</th>
<th>Lower Temp (Fahrenheit)</th>
<th>Upper Temp (Fahrenheit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH_A_EWH</td>
<td>2325</td>
<td>2625</td>
<td>108</td>
<td>111</td>
</tr>
<tr>
<td>WH_A_HP</td>
<td>1725</td>
<td>2550</td>
<td>109</td>
<td>116</td>
</tr>
<tr>
<td>WH_C_EWH</td>
<td>2697</td>
<td>3438</td>
<td>101</td>
<td>107</td>
</tr>
</tbody>
</table>

Table 3.2: WHs A and C upper and lower ET and temperature during Energy service in Critical Peak Event mode.

With upper and lower ET and temperature threshold values shown in Figure 3.2. The result shows that the upper temperature values is different across all three WHs. However, this water draw event have two large water draw volume over 35 gallons within 30 minutes, and the upper and lower ET values was captured after the large water draw. However, WH from Manufacture C have significantly lower temperature value compares to Manufacture A. With the upper temperature threshold from manufacture C being 107°F, it may cause discomfort to some customer.
3.4.3 Energy (Critical Peak Event) Grid-DER Service

This section examines the performance outcomes of WHs during their operation within the Energy service in Critical Peak Event mode. The primary objective of the Energy service is to mitigate energy consumption during peak demand periods on the electrical power grid. As a scheduled service, Critical Peak Event mode is similar to Shed mode, but it reduces even more power consumption during the service period while maintaining customer levels of comfort.

![Figure 3.12: WH A EWH Energy (CPE) Service Result](image)

Similar to Shed mode, in Figures 3.12 and 3.13 are behaved as expected, but in the Critical Peak Event mode these WHs have fewer power activation and its ET values are higher than Shed mode in the service.
Figure 3.14 shows the behavior of WH from Manufacture B during Energy service in Critical Peak Event mode. Its behavior in this mode is similar to the Shed mode such that the WH unit is still not reading ET value correctly.
Figure 3.15 shows WH from Manufacture C under Energy service with Critical Peak Event mode. In this mode WHs C have fewer power activation, also its upper and lower threshold ET values are higher than Shed mode. In this service, the WH unit behave as expected. However, at the beginning of the service where there was a impulse of power activation occurred. Since the duration is only one minute, this kind of behavior is unknown and it did not make any effect in the service.

Table 3.3 shows the upper and lower estimated tank temperature and ET values of WHs from Manufacture A and C. Equation 3.4 was used to calculate the estimated tank temperature on the lower and upper threshold temperature. Even though Critical Peak Event mode in the Energy service is reducing more energy consumption in the duration of the service and raise the ET values, and the upper and lower temperature values did decreased compared to Shed mode. However WHs from Manufacture A still have upper temperature values that is high enough to meet customer’s level of comfort.
### Table 3.3: WHs A and C upper and lower ET and temperature during Energy service in Critical Peak Event mode

<table>
<thead>
<tr>
<th>Water Heater (OEM)</th>
<th>Lower ET (WHR)</th>
<th>Upper ET (WHR)</th>
<th>Lower Temp (Fahrenheit)</th>
<th>Upper Temp (Fahrenheit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH_A_EWH</td>
<td>2775</td>
<td>3150</td>
<td>104</td>
<td>107</td>
</tr>
<tr>
<td>WH_A_HP</td>
<td>1800</td>
<td>2550</td>
<td>109</td>
<td>115</td>
</tr>
<tr>
<td>WH_C_EWH</td>
<td>2665</td>
<td>3808</td>
<td>98</td>
<td>108</td>
</tr>
</tbody>
</table>

3.4.4 **Blackstart Grid-DER Service**

*Blackstart* service is a grid-DER service provides DERs aimed to supporting the recovery of a collapsed electrical power system. It focuses on using energy sources capable of independently supplying power and supporting voltage, as well as managing loads that can defer consumption to a post-recovery period, to help a GO re-energize parts of its balancing area that have experienced a sustained outage. During this service, DCM will send DER *Grid Emergency* command through CTA-2045 to conduct *Blackstart* service to defer power consumption during the service period. Once the period ended then WHs may resume normal operation.
Figures 3.16, 3.17 and 3.19 shows the WHs from Manufactures A and C behavior during Blackstart service. During the Load-up period the WHs behaved as expected by activating
the power to bring the tank temperature to its set point. Under the service period, none of
the WHs power was activated but the ET value were increasing corresponding to the water
draw event. When the service ended, the WHs resume normal operation by activating power
to heat up the tank.

However, in Figure 3.18 the WH from Manufacture B behavior was not expected under Blackstart service. Where at the beginning of the service there were three events of power activation while the unit was under Grid Emergency mode, this behavior it is not expected in this service which makes this unit not conforment.

3.4.5 Remote Water Heater Unit

In this field testing, we also included a remote WH unit situated in a residential home affiliated with one of the Graduate Research Assistant (GRA). This unit was supplied by Manufacturer B. The unit has a set point temperature of $130^oF$ and has a tank capacity of 40 gallons. Unlike the laboratory setup, this unit does not follow a predefined water draw profile; instead, water usage is determined by the resident’s daily consumption patterns. To ensure consistency in our investigation of grid-DER services, all tests on this remote WH were performed using the same methods and duration as those conducted in the laboratory setting. The ensuing figures present the outcomes of each grid-DER service test for the remote WH, showing how it responds under various grid service commands in a real-world environment. This approach not only tests the WH compliance with grid-DER services but also provides insights into its performance in an actual residential setting, reflecting the dynamic interaction between consumer behavior and grid demands.
Figure 3.20: WH B Remote EWH Baseline Service Result

Figure 3.21: WH B Remote EWH Energy (Shed) Service Result
Figures 3.20, 3.21, 3.22, and 3.23 are showcases of remote WH from Manufacture B under Baseline operation, Energy service with Shed and Critical Peak Event mode, and
Blackstart service. During Baseline operation shown in Figure 3.20, this unit behaved normal by activating power after its ET value is increasing, then deactivating its power when ET reaches zero.

However, during Energy and Blackstart services shown in Figures 3.21, 3.22, and 3.23. This unit encountered the same issue as the WH from Manufacture B in the PSU laboratory, where there is incorrect ET reading due to the OEM design on using $A = 1$ as the weighted value and only reading temperature from the lower temperature sensor. As result, this behavior also makes the WH out of conformance. However, during each of the service the water temperature seems to be manageable by the personal experience of the GRA.

3.5 Distributed Energy Resources Management System Aggregation

While grid-DER services are being conducted, the DERMS receives flow reservation parameter messages from all DERs. Having active data from the DERs during these services enables the DERMS to monitor the amount of energy being consumed or conserved by the service.

This DERMS aggregation system will enhance the effectiveness of DR programs by fostering greater engagement between the utility providers and customers. It facilitates improved energy management during peak demand periods, ensuring a more responsive and efficient use of resources.

Based on the established water draw event profile in Table 3.4, an evaluation of two grid-DER services, namely Baseline and Energy (Shed), was performed. This involved all
Table 3.4: Water Draw Event for DERMS grid-DER Service Testing

<table>
<thead>
<tr>
<th>DER_1 Water Draw Event (hh:mm)</th>
<th>1515</th>
<th>1535</th>
<th>1555</th>
<th>1615</th>
<th>1635</th>
<th>1655</th>
<th>1715</th>
<th>1735</th>
</tr>
</thead>
<tbody>
<tr>
<td>DER_2 Water Draw Event (hh:mm)</td>
<td>1520</td>
<td>1540</td>
<td>1600</td>
<td>1620</td>
<td>1640</td>
<td>1700</td>
<td>1720</td>
<td>1740</td>
</tr>
<tr>
<td>DER_3 Water Draw Event (hh:mm)</td>
<td>1525</td>
<td>1545</td>
<td>1605</td>
<td>1625</td>
<td>1645</td>
<td>1705</td>
<td>1725</td>
<td>1745</td>
</tr>
<tr>
<td>DER_4 Water Draw Event (hh:mm)</td>
<td>1530</td>
<td>1550</td>
<td>1610</td>
<td>1630</td>
<td>1650</td>
<td>1710</td>
<td>1730</td>
<td>1750</td>
</tr>
<tr>
<td>Water Draw Amount (Gal)</td>
<td>1</td>
<td>5</td>
<td>6</td>
<td>10</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

four OEM WHs in the PSU laboratory, alongside data capture from one remote WH during these services. The primary aim of this testing was to verify the accuracy and completeness of data acquisition on the DERMS platform while a grid-DER service is being conducted. The outcomes of this testing process presented in Figures 3.24 and 3.25.

Figure 3.24: DERMS Received Data During Grid-DER Service Baseline

Figure 3.24 provides a detailed illustration of the behavior of all DERs during the grid-DER Baseline operation. The first vertical bar indicates the initiation of both the water draw event and the baseline operation. The second vertical bar marks the conclusion of the
water draw event, and the final vertical bar signifies the end of the observation period for the baseline operation. Even though the ET values were different between each WH, WHs from Manufacture A and C were behaved as expected during this Baseline operation, such that each increased of ET is corresponding to the power and water draw event.

But, the Manufacturer B WHs did not behave as expected, when it was towards the end of the water draw event, the Manufacturer B ET value remains constant, which is an unexpected behavior.

![Figure 3.25: DERMS Received Data During Grid-DER Service Energy](image)

Figure 3.25 highlights the behavior of all WHs during the grid-DER Energy (Shed) service. This illustration begins with the first vertical bar, denoting the moment the DERMS issued a Load-up command to DER 15 minutes before the commencement of the service, aimed at pre-heating the WHs to the set point temperature. Subsequently, the second vertical
bar marks the initiation of the Energy Shed service, coinciding with the dispatch of the Shed command to the DER to start the service. The final vertical bar signifies the conclusion of the service, at which point the Endshed command was transmitted to the DER, signaling it to return to normal operational mode. This sequence effectively demonstrates the operational dynamics involved in the Energy Shed service, offering clear insights into the strategic management of energy consumption.

During this service, Manufacturer A and C WHs were behaving as expected to reduce energy consumption by turning on the heating element when ET values reaches to its upper threshold value and turn off the heating element when the ET reaches its lower threshold value. However, the Manufacturer B WH units did not behave as expected with incorrect reading of the ET values. With WHs from manufactures A and C are behaving normally during Baseline operation and Energy service shown in both Figures 3.24 and 3.25, it shows that the power consumption was shifted with time in the Baseline service in Figure 3.25 compared to Baseline operation in Figure 3.24. The energy reduction and shifting show that using DERMS to conduct grid-DER services meets expectation of energy management efficiency.

3.6 Modeling Environment

During the testing of the DERMS sending out the grid-DER services and the DCMs responding back to the DERMS with the DER flow reservation response. Concurrent to the grid-DER service event, the DCMs also send the live Power value from each DER to the
modeling environment server, the purpose of this testing is to gather the behavior on the live data from DERs and conduct a simulation run with those live data and compares it to the actual Power plot of the DER at the end of the service to determine if the results are similar.

3.6.1 Baseline Operation

During Baseline operation, the live Power value was captured and transfer to the ME server to simulate its result for the purpose of comparing real live DER and simulated DER behavior.

Figures 3.26 to 3.33 are the figures that represents the Power values from all lab WHs and its behavior under Baseline operation from Manufacture A, B, and C. As the comparison of each WH power figures between DERMS and ME, the behaviors are nearly identical. Which is expected, because only Power values are being sent to the ME server for simulation on the DER. However, before conducting a large scale simulation in the future, it should eliminate the usage of WH from Manufacture B due to the conformance issue of the unit.

3.6.2 Energy Service

During Energy service in Shed mode, the live Power value was also captured and transfer to the ME server to simulate its result for the purpose of comparing real live DER and simulated DER behavior.

Figures 3.34 to 3.41 are the figures that represents the Power values from all lab WHs and its behavior under Energy service in Shed mode from Manufacture A, B, and C. As the comparison of each WH power figures between DERMS and ME, the behaviors are nearly
Figure 3.26: WH A EWH Baseline operation Power value from DERMS

Figure 3.27: WH A EWH Baseline operation Power value from ME
Figure 3.28: WH A HP Baseline operation Power value from DERMS

Figure 3.29: WH A HP Baseline operation Power value from ME
Figure 3.30: WH B EWH Baseline operation Power value from DERMS

Figure 3.31: WH B EWH Baseline operation Power value from ME
Figure 3.32: WH C EWH Baseline operation Power value from DERMS

Figure 3.33: WH C EWH Baseline operation Power value from ME
identical. Which is expected, because only *Power* values are being sent to the ME server for simulation on the DER. However, before conducting a large scale simulation in the future, it should eliminate the usage of WH from Manufacturer B due to the unit conformance issue.

Figure 3.34: WH A EWH Energy service (Shed) Power value from DERMS
Figure 3.35: WH A EWH Energy service (Shed) Power value from ME

Figure 3.36: WH A HP Energy service (Shed) Power value from DERMS
Figure 3.37: WH A HP Energy service (Shed) Power value from ME

Figure 3.38: WH B EWH Energy service (Shed) Power value from DERMS
Figure 3.39: WH B EWH Energy service (Shed) Power value from ME

Figure 3.40: WH C EWH Energy service (Shed) Power value from DERMS

71
Figure 3.41: WH C EWH Energy service (Shed) Power value from ME
4 Discussion

4.1 Result Summary

The work in this thesis provides a comprehensive examination of the integration of residential DERs into the electric power grid, emphasizing the role of smart electric water heaters in providing DR service. By leveraging these DERs, this study explores innovative strategies to enhance grid flexibility and stability, addressing the pressing challenge of grid instability due to fluctuating energy demands. The findings reveal that integrating DERs not only contributes to stabilizing the grid during peak periods but also plays a role in managing residential energy consumption. This integration is facilitated through the innovative Service-Oriented Architecture framework, which marks a departure from traditional DR programs by prioritizing consumer comfort and autonomy.

A key revelation of this thesis is the potential impact of a consumer-centric approach to DR programs, which could significantly increase participation rates. By granting consumers the flexibility to actively engage in DR programs without facing penalties for opting out, the SOA framework addresses common barriers to participation such as concerns over loss of comfort and control. This approach not only enhances grid management but also fosters a more sustainable and responsive energy ecosystem. The successful implementation of this framework, underscored by the compatibility and interoperability of DERs with existing grid
infrastructure, offers insights for utilities. It provides a practical blueprint for the integration of DERs into energy management strategies, emphasizing the need for DR programs that are both flexible and consumer-friendly. Ultimately, this thesis contributes to the broader discourse on sustainable energy practices, highlighting the role of DERs in promoting grid stability and energy efficiency through enhanced consumer engagement.

4.2 Future Work

The future direction of integrating DERs into the electric power grid, as explored in this thesis, opens up several promising avenues for research and practical application. One key area for future development is enhancing the DCM to act on behalf of the customer. This enhancement would allow the DCM to autonomously align its decisions and actions with the customers’ preferences, making DR programs more personalized and effective. By integrating customer-centric functionalities, this approach aims to streamline automated energy management, ensuring it aligns more closely with individual user needs and expectations.

Another approach can be the expansion of types of DERs involved in DR programs beyond smart electric water heaters. Incorporating a wider range of DERs, including HVAC, PV-inverter system, battery storage, and electric vehicles, could further enhance grid flexibility and resilience. This expansion requires developing algorithms for managing the diverse characteristics and response capabilities of various DERs, ensuring they can effectively contribute to grid stability and energy efficiency.
5 Conclusion

This thesis examines the integration of DERs into residential energy systems, with a spotlight on the SOA framework. At the core of this investigation is the exchange of information between the DERMS and the DERs, mediated through DCMs. These DCMs serve as gateway between DERMS and DERs, enabling the communication that underpins the operation of the system. The research undertook testing across multiple WHs from diverse manufacturers and assessed their alignment with grid service demands, including Baseline, Energy (Shed), Energy (Critical Peak Event) and Blackstart services.

The findings reveal a spectrum of behavioral responses from DERs produced by different manufacturers when engaged in grid service programs. This variability underscores the nuanced challenges of standardizing DER participation in grid services. Despite these challenges, the research underscores features of a service-oriented DERMS: an insight on DER behaviors under grid-DER services and reducing power consumption using grid-DER services. These feature will assist utility to create better energy management system while keeping customer’s level of comfort.

Looking ahead, we can consider a pathway for expanding SOA system capabilities. This includes integrating a broader array of DERs and diversifying the grid service capabilities. Such expansion is important for demonstrating the system scalability and adaptability to a wide range of energy resources and consumer profiles. By doing so, the research aims to
solidify the system’s role as a tool in an energy management system, capable of enhancing grid stability, managing energy consumption, and supporting a more sustainable and efficient use of energy resources.

In summary, this thesis not only contributes valuable insights into the practical deployment of DERs within residential settings, but also charts a course for future innovations in grid service management for DR programs.
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Appendix A: Server Python Script

# DERMS SERVER
# Kai Zeng
# PSU EGoT

import csv
import os
from datetime import datetime
from http.server import BaseHTTPRequestHandler, HTTPServer
from xml.etree import ElementTree as ET

HOST_NAME = '127.0.0.1'
PORT = 8080
DATA_DIR = '/home/sonali'
LOG_FILE = 'comm_derms_csv.csv'
GS_CSV_FILE = 'GS.csv'

class Handler(BaseHTTPRequestHandler):

    def do_POST(self):
        self.send_response(201)
        self.end_headers()
content_length = int(self.headers['Content-Length'])
data = self.rfile.read(content_length).decode("utf-8")

# Parse the incoming XML data
try:
    root = ET.fromstring(data)
    order_id = root.find('Id').text
    customer = root.find('Customer').text
    interval = float(root.find('Interval').text)
    duration = float(root.find('Duration').text)
    power = float(root.find('Power').text)
    energy_take = float(root.find('EnergyTake').text)

    # Get the current timestamp
    current_time = datetime.now().strftime("%Y-%m-%d %H:%M:%S")

    # Create a user profile dictionary for the customer
    user_profile = {
        "Timestamp": current_time,
        "Order ID": order_id,
        "Customer": customer,
        "Interval": interval,
        "Duration": duration,
        "Power": power,
        "EnergyTake": energy_take,
    }
# Write the data to the customer's CSV file

customer_csv_file = os.path.join(DATA_DIR, f"{customer}.csv")

with open(customer_csv_file, 'a', newline='') as csv_file:
    csv_writer = csv.DictWriter(csv_file, fieldnames=user_profile.keys())

    # If the file is empty, write the header row
    if os.path.getsize(customer_csv_file) == 0:
        csv_writer.writeheader()

    csv_writer.writerow(user_profile)

# Log the communication
log_data = [current_time, order_id, customer, interval, duration, power, energy_take]
self.log_communication(log_data)

# Print received data
print(f"Received Order ID: {order_id}")
print(f"Received Customer: {customer}"),
print(f"Received Interval: {interval}"),
print(f"Received Duration: {duration}"),
print(f"Received Power: {power}"),
print(f"Received EnergyTake: {energy_take}\")
print(f"Received Timestamp: {current_time}\")

# Check if the received message is a service
message and print it

message_element = root.find('message')
if message_element is not None:
    service_message = message_element.text
    print(f"Received Service Message: {service_message}\")

if service_message == "Start Service?:"
    gs_csv_file = os.path.join(DATA_DIR, GS_CSV_FILE)
    if os.path.exists(gs_csv_file):
        service_type = self.get_service_type_from_csv(gs_csv_file)
        if service_type:
            response = f"\<Response\>Service Type: {service_type}\</Response\>"
            self.send_response(200)
            self.send_header("Content-type", "text/xml")
            self.send_header("Content-length", str(len(response)))
            self.end_headers()
self.wfile.write(response.encode("utf-8"))

print(f"Sent Response: Service Type: {service_type}\n")

return

else:

print("Failed to retrieve service type from GS.csv")

else:

print("GS.csv does not exist.\n")

except Exception as e:

print(f"Error parsing XML: {str(e)}")

def get_service_type_from_csv(self, file_path):

try:

    with open(file_path, 'r') as csv_file:
        reader = csv.DictReader(csv_file)
        for row in reader:
            if 'ServiceType' in row:
                return row['ServiceType']

except Exception as e:

    print(f"Error reading CSV file: {str(e)}")

    return None

def log_communication(self, data):

    try:
log_file_path = os.path.join(DATA_DIR, LOG_FILE)

with open(log_file_path, 'a', newline='') as log_file:
csv_writer = csv.writer(log_file)
csv_writer.writerow(data)

except Exception as e:
    print(f"Error logging communication: {str(e)}")

if __name__ == "__main__":
    os.makedirs(DATA_DIR, exist_ok=True)

    server = HTTPServer((HOST_NAME, PORT), Handler)
    print(f"Server started on http://{HOST_NAME}:{PORT}")
    try:
        server.serve_forever()
    except KeyboardInterrupt:
        server.server_close()
        print("Server stopped successfully")
Appendix B: Client Python Script

# DCM CLIENT
# Kai Zeng
# PSU EGoT

import os
import requests
import csv
from datetime import datetime

# Define the path to the CSV file
csv_file_path = '/home/pi/client/data.csv'

# Function to read the last row of CSV and extract values
def read_last_row(csv_file_path):
    try:
        with open(csv_file_path, 'r') as csv_file:
            csv_reader = csv.reader(csv_file)
            rows = list(csv_reader)
            if len(rows) >= 2:
                last_row = rows[-1]  # Get the last row
                energy_take = float(last_row[0])
duration = float(last_row[1])
power = float(last_row[2])
interval = float(last_row[3])

return interval, duration, power, energy_take

else:

print(f"Not enough rows in {csv_file_path} to extract data.")

except FileNotFoundError:

print(f"CSV file not found at {csv_file_path}"

except Exception as e:

print(f"Error reading CSV: {str(e)}")

return None, None, None, None

path = os.getcwd()
c_cert_file_path = path + '/cert/client.crt'
c_key_file_path = path + '/cert/client.key'
certServer = path + '/cert/derms.crt'

host_name = 'psupwrlabderms.ddns.net'
host_port = 443
host_address = f'https://{host_name}:{host_port}'

# Function to check service status from the response from the DERMS

def write_service_status(status):

try:
timestamp = datetime.now().strftime('%Y-%m-%d %H:%M:%S')

with open('service_status.csv', 'a', newline='') as csvfile:
    fieldnames = ['Timestamp', 'Status']
    writer = csv.DictWriter(csvfile, fieldnames=fieldnames)

    # If the file is empty, write the header
    if os.stat('service_status.csv').st_size == 0:
        writer.writeheader()

    writer.writerow({'Timestamp': timestamp, 'Status': status})

except Exception as e:
    print(f"Error writing service status to CSV: {str(e)}")

# Function to write service type and timestamp to service_type.csv

def write_service_type(service_type):
    try:
        timestamp = datetime.now().strftime('%Y-%m-%d %H:%M:%S')
        with open('service_type.csv', 'a', newline='') as csvfile:
            fieldnames = ['Timestamp', 'Service Type']
            writer = csv.DictWriter(csvfile, fieldnames=fieldnames)

            # If the file is empty, write the header
            if os.stat('service_type.csv').st_size == 0:
                writer.writeheader()
# Only take the first character after "Service Type: "
first_character = service_type[0] if service_type else ''
writer.writerow({'Timestamp': timestamp,
'Service Type': first_character})

except Exception as e:
    print(f"Error writing service type to CSV: {str(e)}")

# Read values from the last row of CSV
interval, duration, power, energy_take = read_last_row(csv_file_path)

if interval is not None:
    xml = f"""<?xml version="1.0" encoding="UTF-8"?>
<Order>
    <Id>78913</Id>
    <to>gsp</to>
    <from>client</from>
    <Customer>SPC_1</Customer>
    <message>Start Service?</message>
    <Interval>{interval}</Interval>
    <Duration>{duration}</Duration>
    <Power>{power}</Power>
    <EnergyTake>{energy_take}</EnergyTake>
</Order>"""
headers = {'Content-Type': 'application/xml'}
r = requests.post(host_address, data=xml,
verify=certServer, headers=headers,
cert=(c_cert_file_path, c_key_file_path))

print(f"Response from server:
{r.text}")

print(f"Status Code: {r.status_code}")

if 'Service Status: Service Started' in r.text:
    write_service_status('Service Started')

if 'Service Type: ' in r.text:
    service_type = r.text.split
    ("Service Type: ")[1].strip()
    write_service_type(service_type)
else:
    print("CSV values not available, request not sent.")
Appendix C: Grid-DER Service Python Script

# DCM CLIENT
# Kai Zeng
# PSU EGoT

import time
import subprocess
from datetime import datetime

def choose_service():
    print("Choose a service:")
    print("1. baseline")
    print("2. energy-s")
    print("3. energy-c")
    print("4. blackstart")

    while True:
        choice = input("Enter the number corresponding to your chosen service: ")

        if choice in ['1', '2', '3', '4']:
            services = ["baseline", "energy-s", "energy-c", "blackstart"]
```python
selected_service = services[int(choice) - 1]

return selected_service

else:
    print("Invalid choice. Please enter a valid number."

def ask_duration():

    while True:
        try:
            hours =
            float(input("Enter the duration of the service in hours: "))

            if hours > 0:
                return hours * 3600  # Convert hours to seconds
            else:
                print("Please enter a positive number."

            except ValueError:
                print("Invalid input. Please enter a number."

def get_filename(service):

    current_day = datetime.now().strftime("%Y-%m-%d")

    return f"{service}_"{current_day}.txt"

def send_to_tmux(letter, file):

    tmux_command = f"tmux send-keys -t service 'o{letter}' C-m"

    # Execute the tmux command
```
subprocess.run(tmux_command, shell=True)

# Optionally log the command to the file and console
file.write(f"Sent '{letter}' to tmux session 'service'.\n")
print(f"Sent '{letter}' to tmux session 'service'.")

def service_with_initial_l(duration, mid_service_letter, filename):
    with open(filename, "w") as file:
        file.write(f"Service started. Initial 'o' then 'l', followed by 'o' then '
(mid_service_letter)' pattern.\n")

    initial_duration = 30 * 60  # 30 minutes in seconds
    elapsed_time = 0

    while elapsed_time < initial_duration
        and elapsed_time < duration:

            send_to_tmux("o", file)
            time.sleep(5)
            send_to_tmux("l", file)
            time.sleep(900 - 5)
            elapsed_time += 900

    while elapsed_time < duration:

        send_to_tmux("o", file)
        time.sleep(5)
send_to_tmux(mid_service_letter, file)

if (elapsed_time + 900) > duration:
    break

time.sleep(900 - 5)

elapsed_time += 900

send_to_tmux("o", file)
time.sleep(5)

send_to_tmux("e", file)

file.write("Service completed.
")

def main():
    selected_service = choose_service()
    duration = ask_duration()
    filename = get_filename(selected_service)
    print(f"You have selected '{selected_service}' service with a duration of {duration / 3600} hours. Output will be stored in {filename}"
)

if selected_service == "baseline":
    service_with_initial_l(duration, 'e', filename)
elif selected_service == "energy-s":
    service_with_initial_l(duration, 's', filename)
elif selected_service == "energy-c":
    service_with_initial_l(duration, 'c', filename)
elif selected_service == "blackstart":

service_with_initial_1(duration, 'g', filename)

else:

    print("The selected service is not currently implemented in this script.")

if __name__ == "__main__":

    main()
Appendix D: Water Heater Testing Station

Water Heaters From Different OEMs in PSU Water Heater Testing Station.
DCM Mounting onto Water Heater via EcoPort.
DCM Mounted on Water Heater and Activated
Thesis Author and Water Heaters in The Water Heater Testing Station
Thesis Author and Water Heaters in The Water Heater Testing Station. But With Author Conducting a Deep Thought