PNNL-ACT-10136

Energy Northwest — Advanced Grid Interactive Load Efficiency (AGILE)

A Techno-economic Assessment

September 2023

X Ma [1]
D Wu [1]
R Rebich [2]
D McCaughey [3]
R Major [3]
T Barham [4]
D Quintana [4]
K Carbonnier [5]
A Miller [5]

[1] Pacific Northwest National Laboratory
[2] Energy Northwest
[3] UMC
[4] Community Energy Labs
[5] New Buildings Institute

Prepared for Energy Northwest

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <https://www.ntis.gov/about>
Online ordering: http://www.ntis.gov

PNNL-ACT-10136

Energy Northwest — Advanced Grid Interactive Load Efficiency (AGILE)

A Techno-economic Assessment

September 2023

X Ma [1]
D Wu [1]
R Rebich [2]
D McCaughey [3]
R Major [3]
T Barham [4]
D Quintana [4]
K Carbonnier [5]
A Miller [5]

[1] Pacific Northwest National Laboratory
[2] Energy Northwest
[3] UMC
[4] Community Energy Labs
[5] New Buildings Institute

Prepared for Energy Northwest

Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

Chartered in 1957 as a joint operating agency, Energy Northwest (EN) is a consortium of 28 public utility districts (PUDs) and municipalities across Washington state. EN takes advantage of economies of scale and shared services to help utilities run their operations more efficiently and at lower costs, to benefit more than 1.5 million customers. EN develops, owns, and operates a diverse mix of electricity generating resources, including hydro, solar, wind, and battery energy storage projects—and the Northwest's only nuclear energy facility. These projects provide enough reliable, affordable, and environmentally responsible energy to power more than a million homes each year, and carbon-free electricity is provided at the cost of generation. EN continually explores new generation projects to meet its customers' needs.

The Advanced Grid Interactive Load Efficiency (AGILE) project, led by EN, was awarded funding as part of the fourth round of the Clean Energy Fund program administered by the Washington State Department of Commerce to investigate, co-create, and complete a preliminary design for grid-interactive efficient buildings (GEBs) for a number of schools served by Grays Harbor PUD (GHPUD), considering a variety of use cases. Other team members include UMC, Community Energy Labs, New Buildings Institute, and Pacific Northwest National Laboratory (PNNL).

In this project, an initial list of seven schools was identified for consideration. After preliminary evaluation, three schools—Central Elementary, Miller Junior High School, and Hoquiam Middle School—were selected for detailed assessments because they present a rich diversity of challenges and opportunities. For each of the three selected schools, a variety of GEB design options were proposed, focusing on seamlessly integrating electrification, energy efficiency, carbon reduction, and demand response (DR), with some designs also incorporating a battery energy storage system (BESS) to further enhance demand-side flexibility, grid interactivity, and microgrid capability. To facilitate understanding and differentiation, these design options have been categorized into three levels of complexity: *Basic*, *Intermediate*, and *Advanced*. These three tiers reflect the progressive enhancement in energy efficiency and grid-interactive capabilities, providing a structured approach for the envisioned systems.

The techno-economic assessment was led by PNNL, leveraging its advanced modeling and analytical capabilities in building-to-grid integration. The GEB use cases considered in this project include energy charge reduction, demand charge reduction, DR, carbon reduction, and outage mitigation. This report documents the framework for assessing different GEB design options, encompassing an in-depth examination of use cases and value propositions, assumptions and inputs, modeling methods, case studies, as well as key findings. Figure ES.1 summarizes the present value of costs and benefits of different GEB designs for each of the three schools. The following key lessons and implications can be drawn from the study:

1. **Net present value (NPV) costs**

   - For Central Elementary, the Basic GEB design yields the lowest NPV cost primarily because it lacks substantial replacements and additions found in the other two design options, such as air handling units, fan coil units, heat pump domestic hot water heaters, and smart thermostats in addition to replacing existing gas boilers. In addition, the electricity consumption at Central Elementary is lower than the other two schools, thus limiting its potential to benefit from enhanced energy efficiency, DR, and outage mitigation.

   - For Miller Junior High School, considering the outage mitigation benefits, the NPV cost for the Intermediate design that incorporates a BESS is comparable to the Basic design, with a difference of only about 8%.

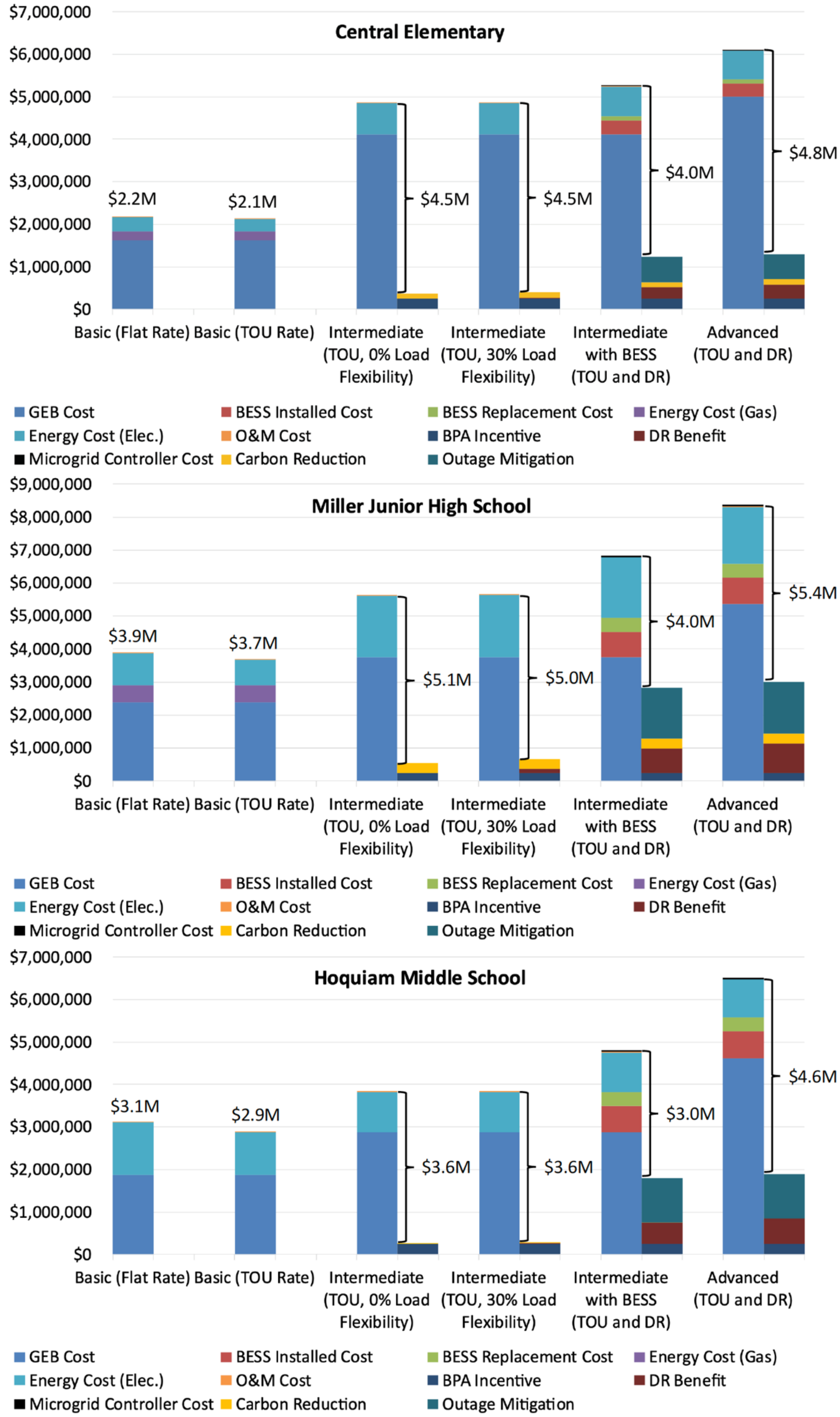

Figure ES.1. Summary of present value costs and benefits

- For Hoquiam Middle School, the Intermediate design that incorporates a BESS emerges as the most cost-effective option, primarily due to its higher electricity load compared to the two schools, which increases the benefits from various use cases and subsequently lowers the net cost.

2. **Energy costs** — For both Central Elementary and Miller Junior High School, the Intermediate and Advanced design options result in higher energy costs compared to the Basic design. This cost increase is primarily due to the fact that electricity is more expensive than natural gas. In addition, for the Basic design, energy costs with the time-of-use (TOU) rate examined in this study is about 5% lower than the existing flat rate. This highlights the opportunity for schools to benefit from adopting TOU tariffs.

3. **DR** — DR programs only offer limited benefits for GEB designs without energy storage. Incorporating energy storage can significantly increase the DR benefits. For example, for Advanced designs that include both BESS and thermal energy storage, the DR benefits increase by 5–9 times compared to the cases without energy storage.

4. **Outage mitigation** — When integrating BESS and microgrid capability, outage mitigation becomes the most valuable use case, followed by DR. The additional benefits outweigh the associated cost of BESS and microgrid.

5. **Carbon reduction** — For Central Elementary and Miller Junior High School, the Intermediate and Advanced designs reduce the schools' carbon footprint by approximately 75% and 78%, respectively, compared to the Basic design. As for Hoquiam Middle School, which is already fully electrified, the Intermediate and Advanced designs lead to relatively smaller carbon reduction—around 5% and 12%, respectively.

6. **GHPUD's benefits** — By embracing the Advanced GEB design option and integrating energy storage with featured DR programs, the selected schools could collectively reduce GHPUD's system peak load by 1,080 kW. This would benefit GHPUD by lowering its operational costs, meeting resource adequacy, deferring infrastructure investments, and contributing to environmental sustainability.

Acknowledgments

We are grateful to Mr. Jeremy Berke, Senior Commerce Specialist and Program Manager for the Clean Energy Fund (CEF) Grid Modernization Program, and Mr. Bob Kirchmeier, former Program Manager for the CEF Grid Modernization Program, for their leadership and support on this and other CEF projects. We are also grateful to Dr. Imre Gyuk, Director of the Energy Storage Program in the Office of Electricity at the U.S. Department of Energy, for providing financial support and leadership on this and related work at Pacific Northwest National Laboratory.

Acronyms and Abbreviations

AGILE	Advanced Grid Interactive Load Efficiency
AHU	air handling unit
BAS	building automation system
BESS	battery energy storage system
BPA	Bonneville Power Administration
CBS	Clean Building Standard
CEF	Clean Energy Fund
CEL	Community Energy Labs
COP	coefficient of performance
DOAS	dedicated outdoor air system
DHW	domestic hot water
DR	demand response
EUI	energy use intensity
FCU	fan coil unit
GEB	grid-interactive efficient building
GHPUD	Grays Harbor PUD
HR	heat recovery
HVAC	heating, ventilation, and air conditioning
ICE	Interruption Cost Estimate
IRA	Inflation Reduction Act
LED	light-emitting diode
LF	load flexibility
MBH	thousands of British thermal units per hour
NBI	New Buildings Institute
O&M	operation and maintenance
PNNL	Pacific Northwest National Laboratory
PUD	public utility district
SAIDI	system average interruption duration index
SAIFI	system average interruption frequency index
TES	thermal energy storage
VAV	variable air volume
VB	virtual battery
VFD	variable frequency drive
WSEC	Washington State Energy Code

Notation

Parameters

d_i	Peak demand of month i
$E_{\text{max}}^{\text{batt}}$	BESS energy capacity
$\underline{E}_k^{\text{vb}}$	VB lower energy limit at hour k
$\overline{E}_k^{\text{vb}}$	VB upper energy limit at hour k
L_k	System native load at hour k
$p_{\text{max}}^{\text{batt}}$	BESS rated power
$\underline{p}_k^{\text{vb}}$	VB lower power limit at hour k
$\overline{p}_k^{\text{vb}}$	VB upper power limit at hour k
α	VB self-discharging rate
β^{dr}	DR incentive rate
ΔT	Time step size
ΔT^{dr}	Required duration for DR
η^+	BESS discharging efficiency
η^-	BESS charging efficiency
γ_i	Demand charge rate of month i
λ_k	Energy charge rate at hour k

Decision Variables

d_i^{net}	Peak demand of month i with energy assets
e_k^{batt}	BESS energy state at the end of hour k
e_k^{vb}	VB energy state at the end of hour k
L_k^{net}	System net load at hour k
p_k^+	BESS discharging power at hour k
p_k^-	BESS charging power at hour k
p_k^{batt}	BESS power output at hour k
$p_k^{\text{batt-dr}}$	BESS power output for DR at hour k
p_k^{dr}	Total power output for DR at hour k
p_k^{tes}	Thermal energy storage power output at hour k
p_k^{vb}	VB power output at hour k

Contents

Figures

Tables

CHAPTER 1

Introduction

The Washington State Clean Energy Fund (CEF), established in 2013, is a publicly funded program that provides grants to support the development, demonstration, and deployment of clean energy technology in Washington state. The Washington State Legislature has authorized $122 million for the fund through its first three rounds of CEF (Washington State Department of Commerce, 2017; Kirchmeier, 2018), including Energy Revolving Loan Fund Grants, Smart Grid and Grid Modernization Grants to Utilities, Federal Clean Energy Matching Funds, and Credit Enhancement for Renewable Energy Manufacturing.

The Grid Modernization program is one among many programs under the umbrella of the CEF (Washington State Department of Commerce, 2023). The program supports innovative grid modernization projects that are designed to advance clean energy technologies and transmission/distribution control system innovations; support renewable energy source integration, distributed energy resource deployment, and sustainable microgrids; and increase utility customer choice in energy sources, efficiency, equipment, and utility services. The program plays a pivotal role by allocating funds to grid modernization initiatives, thereby facilitating Washington in achieving the goal of 100% clean electricity by 2045.

Chartered in 1957 as a joint operating agency, Energy Northwest (EN) is a consortium of 28 public utility districts (PUDs) and municipalities across Washington state. EN takes advantage of economies of scale and shared services to help utilities run their operations more efficiently and at lower costs, to benefit more than 1.5 million customers. EN develops, owns, and operates a diverse mix of electricity generating resources, including hydro, solar, wind, and battery energy storage projects—and the Northwest's only nuclear energy facility. In particular, supported through the second round of CEF, the Horn Rapids Solar, Storage & Training Project in Richland serves as Washington State's first venture into integrating utility-scale solar and battery storage with its clean energy mix, generating enough power to support 600 homes (Ma et al., 2022). These projects provide enough reliable, affordable, and environmentally responsible energy to power more than a million homes each year, and that carbon-free electricity is provided at the cost of generation. EN continually explores new generation projects to meet its customers' needs.

In 2021, the Washington State Department of Commerce announced $3.9 million in grants as part of the fourth round of CEF funding for the early-stage project development of 18 grid modernization projects led by utilities across the state. Among the recipients, the Advanced Grid Interactive Load Efficiency (AGILE) project, led by EN, was awarded to investigate, co-create, and complete a preliminary design for grid-interactive efficient buildings (GEBs) for a number of schools served by Grays Harbor PUD (GHPUD). Other team members include UMC, Community Energy Labs (CEL), New Buildings Institute (NBI), and Pacific Northwest National Laboratory (PNNL). GEBs are also called "smart buildings" because they are characterized by the combination of energy efficiency and demand flexibility with smart technologies and communications to not only inexpensively deliver greater affordability, comfort, productivity, and performance to buildings, but also help utilities manage grid operations and lower system costs.

The primary goal of this project is to establish replicable processes for transforming schools into GEBs. To achieve this goal, an initial list of seven schools was identified for consideration. The project team has worked collaboratively with the schools and GHPUD to understand each stakeholder's unique requirements and developed school selection criteria that address these specific needs. After thorough consideration, three schools have been selected for detailed assessments: Central Elementary, Miller Junior High School, and Hoquiam Middle School, with their geographic locations shown in Figure 1.1. These schools were selected because they present a rich diversity of challenges and opportunities, making them exceptionally well-suited for our focused efforts.

Figure 1.1. School geographic locations

The selected schools are all located in a coastal region with dominant heating needs and relatively mild temperatures throughout the year. While none of them are currently equipped with cooling systems, district staff have noted the possibility of including such equipment in future retrofit projects. Each school includes both a gymnasium and kitchen facilities. Additional attributes of the selected schools are summarized in Table 1.1, where MBH denotes thousands of British thermal units per hour. The averages and peaks of the existing electric load in summer and winter are plotted in Figure 1.2.

Table 1.1. Summary of School Building Characteristics and Heating Systems

	Central Elementary	Miller Junior High	Hoquiam Middle School
Area (sq. ft.)	35,000	88,000	48,000
Number of stories	1	1	2
Gas boiler capacity (MBH)	2×1200	3×1000	—
Electric heating capacity (kW)	—	—	600

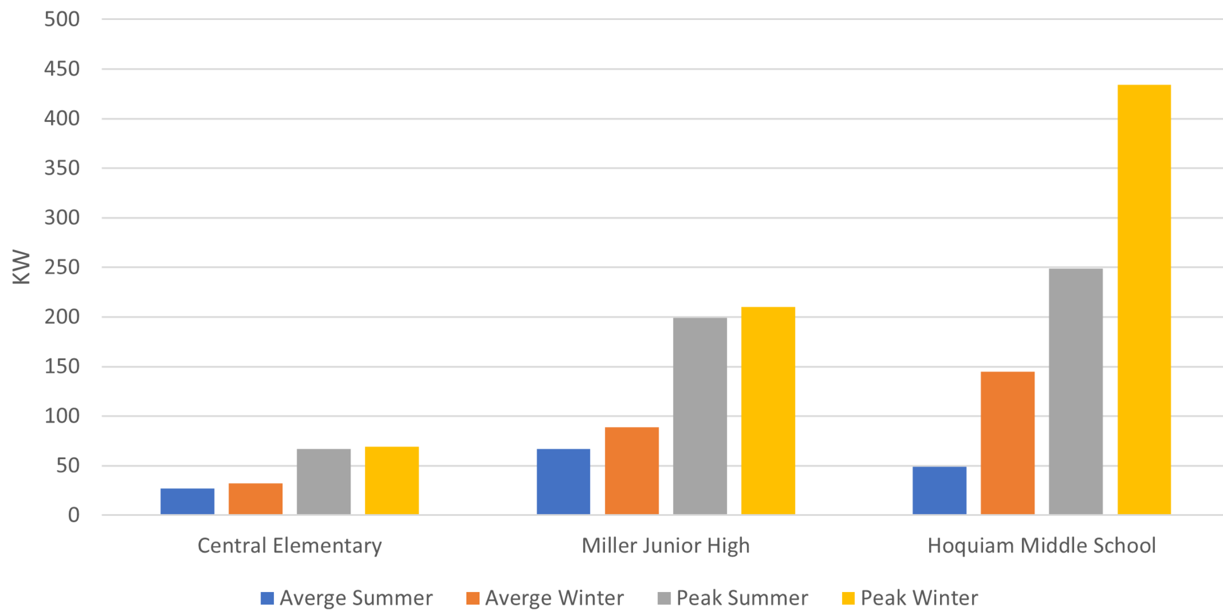

Figure 1.2. Averages and peaks of existing electric load

The morning warm-up of all the school buildings aligns with the utility's peak demand period. In particular, Central Elementary and Miller Junior High School are equipped with natural gas-fired central boilers, which distribute heat through a hydronic loop to a combination of air handling units (AHUs) and/or fan coil units (FCUs). Therefore, both schools have an opportunity for electrification. With current policies advocating for electrification, the focus of these two schools will be on replacing natural gas-fired equipment with equivalent electric alternatives. On the other hand, Hoquiam Middle School has already been equipped with an electrified heating system. This school desires selective equipment replacement and advanced control to deal with its high morning peaks.

The Washington State Energy Code (WSEC) mandates the use of dedicated outdoor air systems (DOASs) with heat recovery (HR). This requirement creates a unique opportunity to decouple ventilation from conditioned air, enabling enhanced grid-interactive capabilities by adjusting power consumption at the zone level without compromising occupant comfort. Adopting electric equipment, efficient components, and advanced control will pave the way for enhanced grid interactivity and more efficient energy management.

Taking into account the unique characteristics and existing conditions of each school, the team developed a preliminary technical design, which includes preferred GEB technology options and considers potential communication and electrical interface requirements, along with sensor needs for control software and its integration with the existing building management system. PNNL led the techno-economic assessment effort, levering its advanced modeling and analytical capabilities in building-to-grid integration to understand the potential benefits of GEB for different grid and/or end-user services. This report presents a thorough techno-economic assessment, encapsulating GEB design options, use cases, modeling and valuation framework, case studies, and concluding remarks.

CHAPTER 2

GEB Design Options

For each selected school, the UMC team has proposed three distinct GEB design options, focusing on seamlessly integrating grid-interactive capability, electrification, energy efficiency, and carbon reduction. The GEB design options were categorized into three tiers: *Basic*, *Intermediate*, and *Advanced*, based on their varying degrees of improvement in grid-interactive capabilities. These tiered GEB design options allow us to customize solutions to align precisely with the unique needs and aspirations of each school.

Key attributes of the three-tier GEB design options are outlined in Table 2.1, where EUI stands for energy use intensity. Note that fossil fuel equipment is only considered in the Basic design for Central Elementary and Miller Junior High School. The corresponding initial costs provide an approximation of the full upgrade costs for each GEB design, which include elements such as audits, design and engineering, equipment selection and purchase, construction management, labor and material for installation, as well as contingency and sales tax expenses. As can be observed, the Basic option offers the advantage of lower initial costs but lacks substantial grid-interactive capability. On the other hand, the Advanced option presents a comprehensive grid-interactive capability, but requires a much higher initial investment cost compared to other alternatives.

Table 2.1. GEB Design Options: Key Attributes

	Basic	*Intermediate*	*Advanced*
Electrification	Retains fossil fuel equipment	HVAC electrification	Full electrification
EUI reduction	<10%	10–20%	>20%
Carbon reduction	Low	Medium	High
Grid-interactive capability	Low	Medium	High
Initial costs	\$1,250,000–\$3,000,000	\$2,500,000–\$4,750,000	\$3,750,000–\$6,250,000
Operational savings	Low	Medium	High

Table 2.2 outlines measures that can be deployed in different designs, where BAS denotes building automation system and VFD denotes variable frequency drive. BAS manages and controls heating, ventilation, air conditioning (HVAC), lighting, and other energy-related systems. VFD is an electrical device used to control and vary the speed and rotational force of an electric motor, which is commonly used to control the speed of motors in various machinery and systems, including pumps, fans, conveyors, and HVAC systems. Note that battery energy storage systems (BESSs) are not included in any GEB design by default. This is due to BESS's unique modularity and flexibility, which allows for seamless integration into diverse

configurations, unlike other GEB measures that often necessitate coordinated deployment. In addition, BESS can also be used for outage mitigation when enabled with microgrid capabilities. In this study, BESS will be incorporated into the baseline Intermediate and Advanced designs to create alternative scenarios with enhanced demand flexibility and grid interactivity, as described in Chapter 5.

Table 2.2. GEB Design Options: Measures

	Basic	*Intermediate*	*Advanced*
LED lighting	✓	✓	✓
Daylighting/Occupancy		✓	✓
Boilers	High-efficient gas	Electric	Electric
Heating coils, distribution piping, DOAS with HR	✓	✓	✓
Pump VFDs	✓	✓	✓
BAS sequence optimization	✓	✓	✓
GEB software		✓	✓
Thermal energy storage			✓

The following sections provide overviews of the school buildings, offer a brief assessment of current conditions, and outline their unique requirements. Specifically, Central Elementary is in need of a full system replacement, Miller Junior High School requires a partial system replacement/upgrade, and Hoquiam Middle School calls for optimization and on-demand replacement. To address the specific challenges and needs of individual schools, the project team proposed a spectrum of GEB design options with different levels of complexity, as elaborated in the following sections.

2.1 Central Elementary

Located in the Hoquiam School District, Central Elementary is a typical example of a building that requires complete replacement of its HVAC, as well as lighting and control systems. Central Elementary is a 35,000-square-foot, single-story school equipped with a gymnasium and kitchen facility. The school's HVAC system currently relies on two 1200 MBH natural gas-fired hot water boilers, which supply hot water at 180°F to two constant-volume AHUs and 18 FCUs. Ten exhaust fans serve the school, and zone control is managed through thermostats. The HVAC units are about 20 years old and require complete replacement, given their rusting and general wear as shown in Figure 2.1. The school's lighting system is also due for replacement. Considering the age of the HVAC equipment and its reliance on fossil fuels, Central Elementary is an ideal candidate for electrification. The complete system overhaul would involve replacing outdated HVAC equipment, lighting, and control systems, significantly improving energy efficiency and overall sustainability. Three GEB design options have been proposed for Central Elementary, as listed in Table 2.3, where DHW denotes domestic hot water.

Figure 2.1. Rooftop HVAC units at Central Elementary

Table 2.3. GEB Upgrade Pathways for Central Elementary

	Basic	*Intermediate*	*Advanced*
Boilers (gas)	✓		
Boilers (electric)		✓	✓
Air-to-water heat pumps			✓
Thermal energy storage			✓
Replacement of hydronic loop piping		✓	
Replacement of heating coils in AHUs and FCUs		✓	
New AHUs and FCUs			✓
DOAS with HR	✓	✓	✓
Heat pump DHW heaters		✓	✓
LED lighting retrofit	✓	✓	✓
Smart thermostats		✓	✓
Advanced building control		✓	✓

2.2 Miller Junior High School

Located in the Aberdeen School District, Miller Junior High is an 88,000-square-foot, single-story school with a gymnasium and kitchen facility. The school's HVAC system was originally operated on electricity but was converted to natural gas in 2005. The HVAC load is currently managed by three 1000 MBH natural gas-fired hot water boilers, installed as part of the 2005 transition from electric to gas. These boilers, operated for nearly 18 years, are approaching their typical service life of 20 years. The boilers supply hot water at 180°F to 60 FCUs located in the attic space. There are no central AHUs in the system. The HVAC system relies on Alerton building automation software for monitoring, with Alerton thermostats being used for temperature control.

Although the natural gas boilers are nearing the end of their lifespan, it is important to note that the hydronic loop and terminal units in the HVAC system remain in good condition and hence do not require replacement. Additionally, the school's control system effectively manages the HVAC operation. In summary, Miller Junior High School requires partial system replacement and presents a promising opportunity for system electrification.

Table 2.4 outlines the proposed GEB design options for Miller Junior High School. Due to the WSEC's requirement for DOAS systems, there could be a significant rework of the ventilation duct work for Miller Junior High since its heating and ventilation are combined in a distributed system of FCUs.

Table 2.4. GEB Upgrade Pathways for Miller Junior High School

	Basic	*Intermediate*	*Advanced*
Boilers (gas)	✓		
Boilers (electric)		✓	✓
Air-to-water heat pumps			✓
Thermal energy storage			✓
Replacement of heating coils in AHUs and FCUs		✓	
New AHUs and FCUs			✓
DOAS with HR	✓	✓	✓
Heat pump DHW heaters		✓	✓
LED lighting retrofit	✓	✓	✓
Smart thermostats		✓	✓
Advanced building control		✓	✓

2.3 Hoquiam Middle School

Hoquiam Middle School requires control optimization and selective equipment replacement. Hoquiam Middle School spans 48,000 square feet and is a two-story school with a gymnasium and kitchen facility. The school's HVAC system is served by nine AHUs, including one split heat pump system for the gymnasium, two AHUs without heating, and six AHUs with electric heating coils. Additionally, the FCUs and variable air volume (VAV) terminal units also have electric heating coils, amounting to a total electric heating capacity of 601.5 kW. Notably, most AHUs were converted to VAV operation in 2011. Therefore, the overall HVAC equipment and distribution system at Hoquiam Middle School are in satisfactory condition. However, certain units may still need replacement or repair.

In addition, the school can benefit from upgrading the building controls. The current control system comprises a mixed version of a MetaSys BACnet controller with some pneumatic devices. The primary issue is the high peak demand during 7 a.m. and 12 p.m. due to the morning startup, as indicated in red in Figure 2.2. Manual adjustments to start HVAC at 4 a.m. may not effectively mitigate these peaks, as illustrated in Figure 2.3 using a representative day. This suggests the need for enhanced controls such as model predictive control (Hao et al., 2018), hierarchical control (Wu et al., 2017), and distributed control (Wu et al., 2017), which could better optimize the equipment operation runtimes while satisfying comfort requirement and mitigating startup peaks. Three GEB design options are proposed for Hoquiam Middle School, as outlined in Table 2.5.

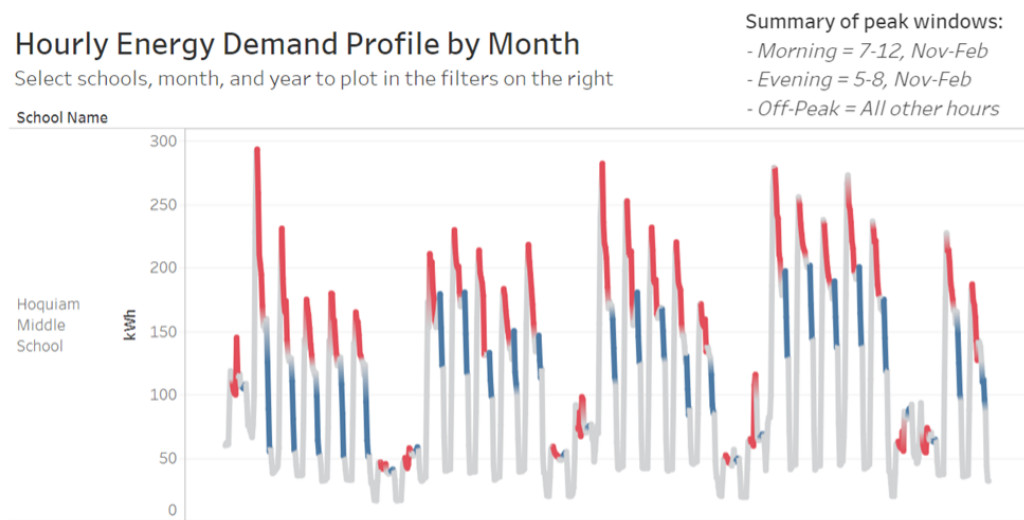

Figure 2.2. Hoquiam Middle School's load profile in December 2019

Table 2.5. GEB Upgrade Pathways for Hoquiam Middle School

	Basic	*Intermediate*	*Advanced*
Thermal energy storage			✓
New heat pump AHUs		✓	✓
DOAS with HR	✓	✓	✓
Heat pump DHW heaters	✓	✓	✓
LED lighting retrofit	✓	✓	✓
Smart thermostats		✓	✓
Advanced building control		✓	✓

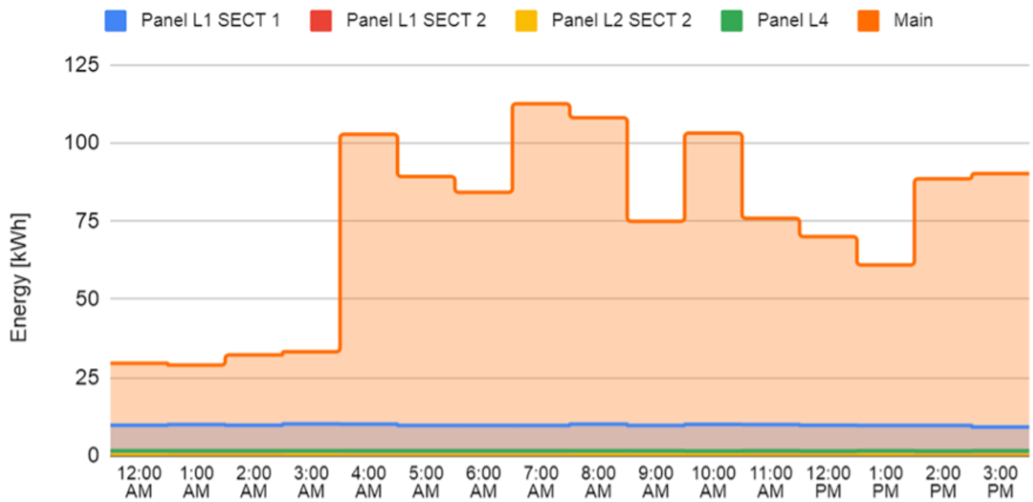

Figure 2.3. Hoquiam Middle School's hourly load on January 21, 2023

2.4 GEB Upgrade Incentives

To support and promote the transition of all selected schools into GEBs, the project team has collected a range of enticing incentives for different equipment types, as shown in Table 2.6. The incentives are sourced from various channels, including the Bonneville Power Administration (BPA), the Inflation Reduction Act (IRA) tax credit catering specifically to non-taxable entities, and the progressive early adopter incentives offered by the Washington State Clean Building Standard (CBS). We note that batteries may be also allowed under a custom grant application, but they are not specifically called out in BPA's Incentive Installation Manual. Embracing these incentives will empower the schools to transition confidently into GEBs, fostering sustainable practices and unlocking numerous benefits for both the schools and the environment.

Table 2.6. GEB Upgrade Incentives

Equipment Type	BPA Incentive	Other Incentives
Air source heat pump	$700 / ton (retrofit)	IRA & CBS
	$150 / ton (upgrade)	
AHUs & FCUs	$300 / horsepower	CBS
Thermal energy storage	Custom grant	IRA & CBS
Batteries with control systems	N/A	IRA

CHAPTER 3

Use Cases

Flexible building loads, especially those in commercial buildings, represent a significant but largely untapped resource for addressing resource adequacy and flexibility challenges in the evolving grid (Wu et al., 2018; Huang et al., 2021). It has shown that commercial HVAC systems can be effectively controlled to follow the grid dispatch signals in real-time (Wang et al., 2021). Energy storage can store energy produced at one time for use at a later time, and thereby provide various grid and end-user services, including bulk energy, ancillary, transmission, distribution, and customer energy management services (Balducci et al., 2018). Integrating flexible building loads with energy storage enhances demand-side flexibility beyond the sum of their individual capabilities (Hao et al., 2018). Through effective management and coordination (Ma et al., 2020), these systems can be optimized to fully use their collective capabilities and maximize the potential to benefit both customers and the grid (Wu et al., 2022). A list of high-value end-user applications was identified in this study to benefit the three selected schools, including energy charge reduction, demand charge reduction, demand response (DR), carbon reduction, and outage mitigation, which are briefly described as follows.

3.1 Energy Charge Reduction

Energy charge is determined based on the total energy consumed and the timing of energy consumption. It is mainly designed to reflect the operational cost of electricity generation and delivery. GEBs offer opportunities to lower the energy charge from multiple perspectives. First, GEBs enhance energy efficiency, which directly correlates to reduced energy consumption and lower energy costs. By utilizing intelligent systems and automation, these buildings are designed to minimize energy consumption, which can result in significant savings. Second, GEBs bring an added layer of demand flexibility and control, enabling energy shifting. This means that energy consumption can be strategically adjusted to take advantage of lower rates during off-peak hours, or to reduce load during peak periods when energy is most expensive. When paired with energy storage, this capability is significantly amplified, opening up even greater opportunities for cost savings under dynamic pricing or time-of-use (TOU) rates.

3.2 Demand Charge Reduction

Demand charge is determined based on the maximum power consumption during certain times on weekdays and weekends within a billing period (typically a month). It is mainly designed to recover the investment in electricity generation and transportation infrastructure. Separating demand charge from energy charge helps fairly distribute power system’s operation and investment cost to customers. GEBs also bring a significant advantage in reducing the peak demand and associated demand charges. The inherent flexibility allows for real-time adjustments to power consumption, reducing usage during peak hours or periods of grid stress.

When energy storage is integrated into GEBs, the capability for managing peak demand is elevated even further. The increased flexibility offered by energy storage enables more strategic decisions about when to consume, store, or discharge energy. Advanced control can be used to automate decision-making and optimize performance.

3.3 Demand Response

DR has the potential to be a cost-effective tool to reach its aggressive renewable energy goals while maintaining the reliability of power grids (Wu et al., 2021). Customers can participate in DR programs offered by utilities to compensate them for curtailing their energy during peak hours. A participating customer is typically compensated based on DR capacity and the amount of energy curtailed during DR events. The rules and incentives may vary by DR program. Active participation in DR programs serves a dual purpose. For utilities, it provides an efficient way to lower peak demand and helps address challenges associated with resource and transmission adequacy. For consumers, it offers a financial incentive to respond to grid needs, thereby reducing their overall energy costs.

GEB designs help increase schools' DR capability and increase their DR revenue. By utilizing smart building systems and automation, these buildings can more easily adapt to real-time energy management, facilitating optimal energy reduction. The integration of energy storage allows schools to further adjust and optimize their consumption, increasing the DR capability that schools can offer.

3.4 Carbon Reduction

Carbon reduction focuses on strategies to decrease the emission of carbon dioxide (CO_2) and other greenhouse gas emissions released into the atmosphere. The overarching aim is to mitigate the adverse effects of climate change by limiting the accumulation of these gases, which contribute to rising global temperatures and associated environmental disruptions. Carbon reduction is a cornerstone in international endeavors to combat climate change and stave off its most damaging consequences.

GEBs play a significant role in this context by offering features that boost energy efficiency and lower EUI. Utilizing smart building systems, automated controls, and real-time energy management, GEB designs can adapt to varying conditions to minimize energy use. This not only leads to reduced energy consumption and costs but also contributes to lowering carbon emissions. Furthermore, the electrification of building systems presents another avenue for carbon reduction. By transitioning from gas boilers to electric boilers, buildings are better aligned with the clean energy landscape of Washington State, where a significant percentage of electricity comes from low-carbon and renewable sources. This shift away from fossil fuel-based systems to electric ones allows buildings to tap into this cleaner grid, making the use of energy more sustainable and contributing to carbon reduction efforts.

3.5 Outage Mitigation

Resilience has become a high priority for federal, state, and local governments, and is moving into the industrial and commercial sectors (Wu et al., 2020). Developments and advances in GEB and various distributed energy resources attached to buildings make them valuable assets in microgrids (Balducci et al., 2020). Outage mitigation refers to the strategies and measures taken to prevent or minimize the impact of power outages, which may occur due to various reasons, such as natural disasters, equipment failures, maintenance issues, and grid instability. Outage mitigation focuses on reducing the interruptions caused by outages and ensuring the reliability and continuity of essential services.

Smart school buildings that are paired with BESSs can be incorporated into microgrid plans. A microgrid is generally defined as a small network of electricity users that take advantage of a localized supply of electricity, enabling the network to disconnect from the centralized power grid and operate in an islanding mode. Microgrid controllers and associated upgrades are also needed to enable islanding and transitioning between grid-connected mode and island mode. When a school building is microgrid capable, the synergy between its BESS and other GEB capabilities becomes particularly impactful. In the event of a main grid outage, such a design allows the school to serve its local load autonomously. Advanced control systems, including various learning-based methods such as Du and Wu (2022) and Das et al. (2022), can be used to coordinate BESS with other building assets to optimize energy usage, prioritizing critical loads and extending the duration of autonomy during an outage. This not only enhances the resilience of the school's energy system but also contributes to broader community resilience by potentially serving as a local energy hub during emergencies.

CHAPTER 4

Modeling and Valuation Methods

The benefits associated with different GEB upgrade pathways highly depend on the associated technical characteristics and physical capabilities. Advanced modeling and analytical methods are required to appropriately represent flexible load and energy storage in various use cases and define the technically achievable benefits (Wu and Ma, 2021). It is crucial to develop well-balanced models that can reasonably represent these technical characteristics while maintaining a level of simplicity for ease of use and interpretation. Co-optimizing stacked value streams (Wu et al., 2015) is crucial for enhancing the cost-effectiveness and financial sustainability of GEB projects. The modeling and analysis in this study build upon PNNL's existing expertise, leveraging BESS models from previous CEF projects and load flexibility models from previous building-to-grid integration projects.

4.1 Modeling of Individual Energy Assets

4.1.1 Flexible Building Load

In this study, the aggregate flexibility of individual buildings is characterized and modeled using the virtual battery (VB) method (Wu et al., 2020). The VB model employs a scalar linear system that resembles simplified battery dynamics parameterized by charging/discharging power limits, energy limits, and self-discharging rate, as given in (4.1):

$$e_{k+1}^{\text{vb}} = (1-\alpha)e_k^{\text{vb}} - p_k^{\text{vb}}\Delta T, \quad \forall k \in \mathcal{K}, \tag{4.1a}$$

$$\underline{p}_k^{\text{vb}} \le p_k^{\text{vb}} \le \overline{p}_k^{\text{vb}}, \quad \forall k \in \mathcal{K}, \tag{4.1b}$$

$$\underline{E}_k^{\text{vb}} \le e_k^{\text{vb}} \le \overline{E}_k^{\text{vb}}, \quad \forall k \in \mathcal{K}, \tag{4.1c}$$

where p_k^{vb} is the charging/discharging power of VB at hour k, e_k^{vb} is the energy state, α is the self-discharging rate, $\underline{p}_k^{\text{vb}}$ and $\overline{p}_k^{\text{vb}}$ are power limits, and $\underline{E}_k^{\text{vb}}$ and $\overline{E}_k^{\text{vb}}$ are energy limits.

In this VB model, the charging/discharging power corresponds to the deviation of total power consumption from the baseline, the energy state corresponds to the average energy state of the HVAC load, and the self-discharging rate captures the leaking energy. This model captures the inherent ability of buildings to store heat in thermal mass, vary their power consumption, and shift their electric energy consumption to an earlier or later off-peak time, subject to customer requirements for comfort and convenience.

4.1.2 Thermal Energy Storage

Thermal energy storage (TES) is a cost-effective method to help balance loads and reduce the operation of a building's heating and cooling equipment during peak demand periods. TES involves using an insulated tank to store thermal energy, either in the form of hot or cold water, which can then be utilized in a building's hydronic heating or cooling system.

The schools featured in this report are heating dominated, and their peak demand occurs during the morning warm-up period. In such cases, the thermal storage tank is charged during off-peak hours to store thermal energy for use during the morning warm-up phase. This enables the building's heating system to draw from the tank instead of relying on the boiler or heat pump to provide hot water to the AHUs and terminal units. By utilizing energy from the tank, the boiler or heat pump can be shut down, thereby avoiding any additional demand on the grid.

UMC has conducted an evaluation to assess the results of TES modeling, using Miller Junior High School as a test case. These findings are outlined as follows and could be applied to all three schools in regard to the utilization of TES.

Table 4.1. Simulated GEB Configurations for Miller Junior High School

GEB Design Option	System Configuration
Basic	Condensing boilers (with 93% efficiency)
Intermediate	Air source heat pumps (COP = 3)
Advanced	Air source heat pumps (COP = 3) and 2000-gallon TES

All GEB design options have been simulated by UMC for Miller Junior High School, where detailed system configurations can be found in Table 4.1. In the Intermediate and Advanced scenarios, an average coefficient of performance (COP) of 3 was assumed for all air-source heat pumps. Several key findings were summarized as follows:

- In the Basic scenario, condensing boilers still demonstrated the best annual utility costs at the current utility rate due to relatively low gas prices.
- The Advanced scenario, which reduced peak heating demand by 40% and utilized off-peak hours for TES charging, could save approximately $13,000 annually compared to the Intermediate scenario. With TES, the overall demand reduction in the Advanced scenario was estimated at around 30%.

Based on these calculations, it could be assumed that in the Advanced scenario, an optimally sized TES could provide a 30% capability for demand reduction across all selected schools in the subsequent economic analysis.

4.1.3 Battery Energy Storage

A BESS can be modeled as a scalar linear dynamical system that resembles simplified energy state dynamics parameterized by charging and discharging power limits, energy state limits, and efficiencies (Wu et al., 2021). To capture one-way efficiencies, two non-negative auxiliary variables p_k^+ and p_k^- can be introduced to represent discharging and charging power at the point of common coupling, respectively. The discharging and charging power ranges are given by:

$$0 \le p_k^+ \le p_{\mathrm{max}}^{\mathrm{batt}}, \quad 0 \le p_k^- \le p_{\mathrm{max}}^{\mathrm{batt}}, \quad \forall k \in \mathcal{K}, \tag{4.2}$$

where $p_{\mathrm{max}}^{\mathrm{batt}}$ is the BESS rated power and $\mathcal{K}$ is a set that contains all scheduling hours. Thus, the BESS power output can be expressed as:

$$p_k^{\mathrm{batt}} = p_k^+ - p_k^-, \quad \forall k \in \mathcal{K}, \tag{4.3}$$

where a positive p_k^{batt} means discharging. The dynamics of the BESS energy state can be modeled as:

$$e_k^{\mathrm{batt}} = e_{k-1}^{\mathrm{batt}} - (p_k^+/\eta^+ - p_k^- \eta^-)\Delta T, \quad \forall k \in \mathcal{K}, \tag{4.4}$$

where e_k^{batt} is the energy state at the end of hour k, η^+ and η^- are discharging and charging efficiencies, respectively, and ΔT represents 1 hour.

4.2 Estimation of Gas Heating Load

In addition to the existing electricity load, the heating load profiles at Central Elementary and Miller Junior High School are also required to compare gas and electric heating options. As the historical hourly data is not available, we estimated the hourly gas heating load for both schools using PNNL's Prototype Building Models (DOE, Office of EERE, 2023). These models were developed for estimating energy usage and load profiles for different building types, including both residential and commercial buildings. Utilizing these models allows us to simulate the gas heating load at the two schools based on their respective building characteristics, weather conditions, and other relevant parameters. Although these models provide a validated and standardized method for estimating the schools' heating load, they may not capture every unique circumstance. To improve accuracy and reliability, the results were calibrated using the historical monthly gas consumption. The heating load estimation procedures are outlined as follows:

1) The "Standard 90.1–2019" datasets under the "Commercial" section were used. In particular, the "Primary School" and "Secondary School" models were used to simulate the Central Elementary and Miller Junior High School, respectively.

2) The building models in Port Angeles, WA were selected as it is the closest location to the selected schools in the dataset.

3) Hoquiam AP's TMY3 weather data was used.

4) EnergyPlus (EnergyPlus, 2023) was used to simulate the school buildings with the selected models and weather data.

5) The gas heating load results from EnergyPlus were scaled to account for area discrepancies between the building models and the actual schools, and then calibrated using the historical monthly gas consumption.

Once the simulated hourly gas heating load is obtained from EnergyPlus, additional post-processing steps were carried out to estimate the gas consumption and electric heating load, as shown in Figure 4.1.

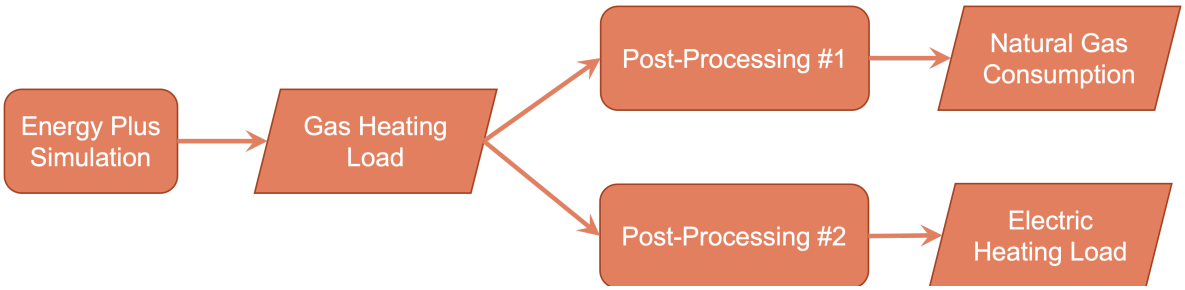

Figure 4.1. Procedures for estimating gas consumption and electric heating load

4.3 Valuation Methods

4.3.1 Energy Charge, Demand Charge, and Demand Response

4.3.1.1 Energy and Demand Charge Reduction

Given the native load profile, the peak demand of month i can be calculated and denoted as d_i. The combination of BESS, VB, and TES can be utilized to reduce the peak demand. With these energy assets, the system net load can be expressed as:

$$L_k^{\text{net}} = L_k - p_k^{\text{batt}} - p_k^{\text{vb}} - p_k^{\text{tes}}, \ \forall k \in \mathcal{K}, \tag{4.5}$$

where L_k is the native load at hour k, and p_k^{tes} is the TES power output at hour k. Therefore, the savings in annual demand charge can be expressed as:

$$B^{\text{DC}} = \sum_{i=1}^{12} \gamma_i \left(d_i - d_i^{\text{net}} \right), \tag{4.6}$$

where γ_i is the demand charge rate of month i and d_i^{net} is the peak demand of month i with BESS, which can be further expressed as:

$$d_i^{\text{net}} = \max \left(d_{\text{min}}, \max(L_k^{\text{net}} : k \in \mathcal{J}_i) \right), \tag{4.7}$$

and $\mathcal{J}_i$ is a set that contains all hours of month i. In comparison, the savings in annual energy charge only depend on the change of import energy:

$$B^{\text{EC}} = \sum_{k \in \mathcal{K}} \lambda_k \left(L_k - L_k^{\text{net}} \right) \Delta T, \tag{4.8}$$

where λ_k is the energy charge rate at hour k.

4.3.1.2 Demand Response

The combination of BESS, VB, and TES also has the opportunity to receive incentives for participating in DR programs. Payment for this service can be calculated based on GEB's response relative to a baseline. In particular, the BESS can be optimally dispatched to maximize its potential DR benefits.

DR requires an automatic reduction of load or increasing of generation for a short duration upon an under-frequency event. The payment depends on how much a GEB changes its power from the operating point prior to a DR event. For BESS, the amount of power for DR services should be nonnegative and constrained by its rated power:

$$0 \leq p_k^{\text{batt-dr}} \leq p_{\text{max}}^{\text{batt}}, \ \forall k \in \mathcal{K}. \tag{4.9}$$

Enough energy also needs to be reserved to ensure a BESS can last the required duration:

$$e_k^{\text{batt}} \geq p_k^{\text{batt-dr}} \Delta T^{\text{dr}} / \eta^+, \ \forall k \in \mathcal{K}, \tag{4.10}$$

where ΔT^{dr} is the required duration for DR services. To simplify the analysis, we will use the average capacity reserved for DR in a month to determine the monthly payment. Therefore, when BESS is combined with VB and TES, the total DR capacity can be expressed as:

$$p_k^{\text{dr}} = p_k^{\text{batt-dr}} + p_k^{\text{vb}} + p_k^{\text{tes}}, \ \forall k \in \mathcal{K}, \tag{4.11}$$

and the annual DR benefits can be calculated by:

$$B^{\text{DR}} = \sum_{i=1}^{12} \left(\beta^{\text{dr}} \sum_{k \in \mathcal{J}_i} \frac{p_k^{\text{dr}}}{|\mathcal{J}_i|} \right), \tag{4.12}$$

where β^{dr} denotes the DR incentive rate.

4.3.1.3 Optimal Dispatch

The optimal dispatch problems can be formulated as:

$$\begin{aligned} \mathbf{P}: \quad & \text{maximize} \quad B^{\text{DC}} + B^{\text{EC}} + B^{\text{DR}} \\ & \text{subject to} \quad (4.2) - (4.12). \end{aligned}$$

Note that the objective functions and all constraints in these problems are linear functions of decision variables except (4.7), where the max operators are nonlinear. To linearize (4.7), the monthly peak demand d_i^{net} can be expressed as an epigraph term:

$$d_i^{\text{net}} \geq d_{\text{min}}, \ d_i^{\text{net}} \geq L_k^{\text{net}}, \ \forall i \in \mathcal{I}, \ \forall k \in \mathcal{J}_i, \tag{4.13}$$

where $\mathcal{I} = \{1, \cdots, 12\}$. By applying these inequality constraints, we obtain an LP problem:

$$\begin{aligned} \mathbf{P}_{\text{LP}}: \quad & \text{maximize} \quad B^{\text{DC}} + B^{\text{EC}} + B^{\text{DR}} \\ & \text{subject to} \quad (4.2) - (4.6), \ (4.8) - (4.13). \end{aligned}$$

Note that inequality constraint (4.13), together with the maximization in the objective function, ensures that the obtained LP problem is equivalent to the original formulation. In this analysis, we solved optimization problem $\mathbf{P}_{\text{LP}}$ for all selected schools to determine their annual benefits received from energy and demand charge reduction, as well as DR services. These benefits were then converted into the present value, aiding us in assessing the cost-effectiveness of deploying different GEB design options.

In practice, there exist various operational uncertainties and forecasting errors, especially those related to weather and load. Although advanced stochastic (Huang et al., 2023) and rule-based methods (Wu et al., 2022) are available to address these uncertainties, this study was primarily designed to meet the planning needs and hence did not explicitly model these uncertainties. Nevertheless, the potential impacts of these uncertainties such as increased battery cycling and attenuated demand reduction effectiveness were implicitly considered.

4.3.2 Carbon Reduction

The benefits associated with carbon emission reduction can be assessed based on a carbon tax or the cost in a cap-and-trade system for emission allowances. In this study, the potential benefits from reducing carbon emissions were quantified using carbon tax, which is a policy tool adopted by governments to incentivize the reduction of CO_2 and other greenhouse gas emissions by pricing the carbon content of fossil fuels.

To carry out the carbon reduction assessment, we assigned a distinct EUI reduction level for each GEB design option. More precisely, drawing from the EUI reduction attribute presented in Table 2.1, we established the assumption that the EUI across all schools could be lowered to 90% for the Basic design, 85% for the Intermediate design, and 75% for the Advanced design, respectively.

Secondly, according to the results of the second auction of allowances for carbon emissions conducted by the Washington State Department of Ecology, the carbon tax rates in Washington State have increased to $56.01 per metric ton of CO_2 in 2023 (Washington Policy Center, 2023). Furthermore, this project adopted the emission rates for natural gas and electricity generation based on statistics from the U.S. Environmental Protection Agency (EPA, 2023) and BPA (Electricity Maps, 2023). These emission rates were estimated at 0.97 pounds per kWh and 0.18 pounds per kWh, respectively, approximately 0.44 and 0.08 kilograms per kWh. With these emission rates, we could calculate carbon emissions resulting from all GEB designs and assess the carbon reduction of other designs compared to the Basic design.

4.3.3 Outage Mitigation

In this project, we monetized outage mitigation services based on the cost of unserved load. GHPUD outage statistics provided in (Grays Harbor PUD, 2023) are shown in Figure 4.2. The system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI) in 2022 are 850 and 2.4, respectively. The average duration per outage is about 354 minutes (850/2.4) or six hours. Additionally, GHPUD serves 5,050 commercial and 38,570 residential customers. It is assumed that each school experiences three outages annually, with each outage lasting for six hours.

These numbers were then fed into the Interruption Cost Estimate (ICE) calculator (Lawrence Berkeley National Laboratory, 2018) to estimate the cost of unserved load. The estimated cost of unserved load was $30.51 per kWh for medium and large customers, as listed in Figure 4.3. This cost was utilized in a post-processing step to quantify the benefits of outage mitigation.

	Totals 2022	Totals 2021	Previous 5 Yr Avg	Change
Outages	**278**	312	312	▼ -11%
Interruptions	**105,949**	102,091	69,262	▲ 53%
Customer Hours	**626,193**	368,833	239,927	▲ 161%
SAIDI (Min / Cust)	**850**	507	338	▲ 152%
*	**169**	201	148	▲ 14%
SAIFI (Int / Cust)	**2.4**	2.3	1.6	▲ 48%
*	**0.9**	1.3	1.0	▼ -5%

* Excluding Major Event Days

Figure 4.2. GHPUD outage statistics

Sector	# of Customers	Cost Per Event (2016$)	Cost Per Average kW (2016$)	Cost Per Unserved kWh (2016$)	Total Cost (2016$)
Residential	43,620	$13.66	$9.21	$1.56	$1,430,429.46
Small C&I	4,650	$3,707.38	$877.75	$148.69	$41,374,311.55
Medium and Large C&I	400	$26,733.17	$180.11	$30.51	$25,663,845.33
All Customers	**48,670**	**$586.16**	**$198.47**	**$33.62**	**$68,468,586.34**

Figure 4.3. Estimated cost of unserved load by customer type

CHAPTER 5

Case Studies and Inputs

5.1 Case Studies

The following case studies were carried out to understand the potential benefits and cost-effectiveness associated with different GEB design options and load flexibility (LF) enhanced through advanced controls.

- The Basic GEB design with 10% EUI reduction.
- The Intermediate GEB design with 15% EUI reduction, characterized by different demand-side flexibility from load or BESS:
  - zero LF;
  - 30% LF (load can be reduced by 30% below the peak level at the maximum);
  - 30% LF and BESS with microgrid capabilities.
- The Advanced GEB design with 25% EUI reduction, paired with both BESS and TES, featuring 30% LF and microgrid capabilities.

Each scenario was evaluated under both flat and TOU rate schedules. The first case with the Basic design serves as a benchmark to underscore cost and benefit variations, determine net-cost changes and assess the economic attractiveness of alternative designs.

5.2 GEB Costs

The GEB design options for the selected schools are assumed to have an economic life of 20 years, and a discount rate of 6.8% is considered. The inflation rate for both energy and annual operation and maintenance (O&M) costs is assumed to be 5%.

Table 2.1 reveals considerable variability in the capital costs for each GEB design option. For a more precise economic assessment, extensive efforts have been made to refine the cost estimates for each school and its corresponding GEB option. The refined estimates have been rounded to the nearest $250,000, as listed in Table 5.1. The average value of the refined cost ranges outlined in Table 5.2 will be used in the techno-economic assessment.

Table 5.1. GEB Cost Ranges by School

School	GEB Design	Low Range	High Range
	Basic	$1,250,000	$2,000,000
Central Elementary	*Intermediate*	$3,500,000	$4,750,000
	Advanced	$4,250,000	$5,750,000
	Basic	$1,750,000	$3,000,000
Miller Junior High School	*Intermediate*	$3,000,000	$4,500,000
	Advanced	$4,500,000	$6,250,000
	Basic	$1,500,000	$2,250,000
Hoquiam Middle School	*Intermediate*	$2,500,000	$3,250,000
	Advanced	$3,750,000	$5,500,000

Table 5.2. GEB Costs Used in Economic Assessments

School	*Basic*	*Intermediate*	*Advanced*
Central Elementary	$1,625,000	$4,125,000	$5,000,000
Miller Junior High School	$2,375,000	$3,750,000	$5,375,000
Hoquiam Middle School	$1,875,000	$2,875,000	$4,625,000

5.3 BESS Parameters and Microgrid Cost

For this economic assessment, li-ion BESS was considered in the Intermediate and Advanced GEB design options. The desired rated power and energy capacity of BESS may vary from one school to another, depending on the load characteristics. While advanced sizing methods such as Wu et al. (2017) and Wu et al. (2016) could be used to determine the optimal BESS sizes for different school buildings, this project employs a simplified approach by using 3-hour BESSs with their rated power determined based on each building's peak load. Such an approach aligns with the project's primary focus on GEB designs without delving into comprehensive BESS sizing analyses. This allows us to concentrate on GEB assessment while also considering the implications of incorporating BESS. Specifically, the following BESS sizes were used in this study:

- Central Elementary: 200 kW/600 kWh,
- Miller Junior High School: 500 kW/1500 kWh,
- Hoquiam Middle School: 400 kW/1200 kWh.

The rated power is set slightly higher than the maximum load to provide a margin for potential load growth or uncertainties.

The BESS parameters were adopted from PNNL's Energy Storage Cost and Performance Database (Pacific Northwest National Laborotary, 2023). In particular, the total installed cost of the BESS was assumed to be $520/kWh with a round-trip efficiency of 95%. Each BESS is expected to last 13 years with a cycle life of 2500 cycles before requiring a replacement. The control and communication cost associated with microgrid is reviewed in Giraldez et al. (2018). This study assumes that the microgrid enabling cost is at 7% of the total BESS installed cost.

5.4 Electricity Load

The 2019 hourly load profiles for the three schools were obtained. To show the daily electricity load fluctuation in summer and winter, Figures 5.1–5.3) present Seasonal boxplots of hourly load for each of the three schools. Key observations and insights are offered as follows.

- Central Elementary stands out with the lowest electricity load among the three selected schools. During the summer season, its average hourly load hovers around 27 kWh, while in winter, it increases slightly to approximately 32 kWh. In terms of peak loads, the school experiences a summer peak of 67 kWh, which occurs at 12 p.m. In comparison, the winter peak reaches 69 kWh and occurs at 11 a.m.

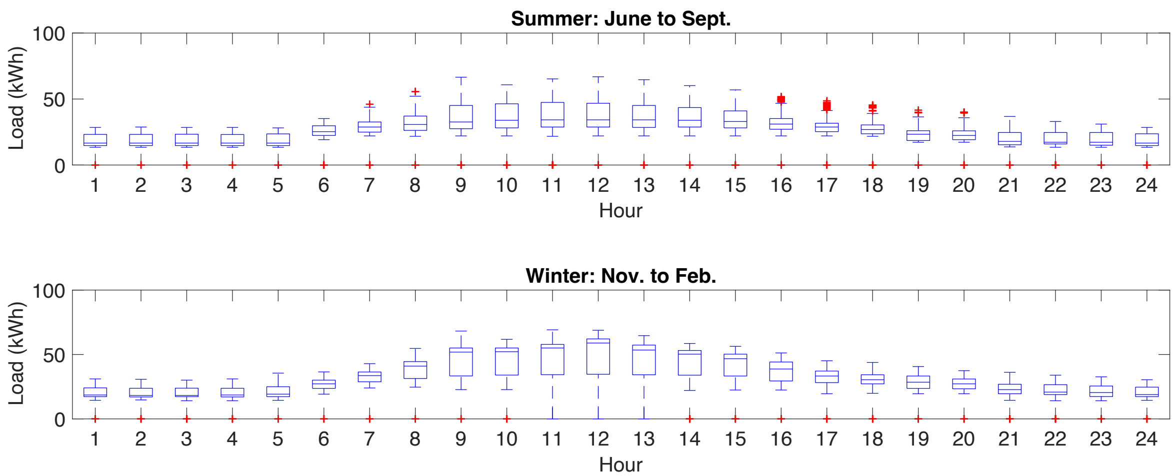

Figure 5.1. Seasonal boxplot of hourly electricity load at Central Elementary

- Miller Junior High School exhibits higher electricity loads compared to Central Elementary. During the summer season, its average hourly load stands at approximately 67 kWh, while in winter, it rises to around 89 kWh. Both its summer and winter peaks occur at 12 p.m., with the summer peak reaching 199 kWh and the winter peak slightly higher at 210 kWh.

- Hoquiam Middle School has the highest electricity load profile among all the three selected schools, primarily due to its electrified HVAC system. Notably, the school's average summer load is 49 kWh, but this value experiences a substantial surge to 145 kWh during the winter season. Its summer peak occurs at 8 a.m. and reaches 249 kWh, while the winter peak is significantly higher at 434 kWh and occurs at 5 a.m. This suggests that the school has implemented efforts to shift its peak load to early winter mornings for preheating.

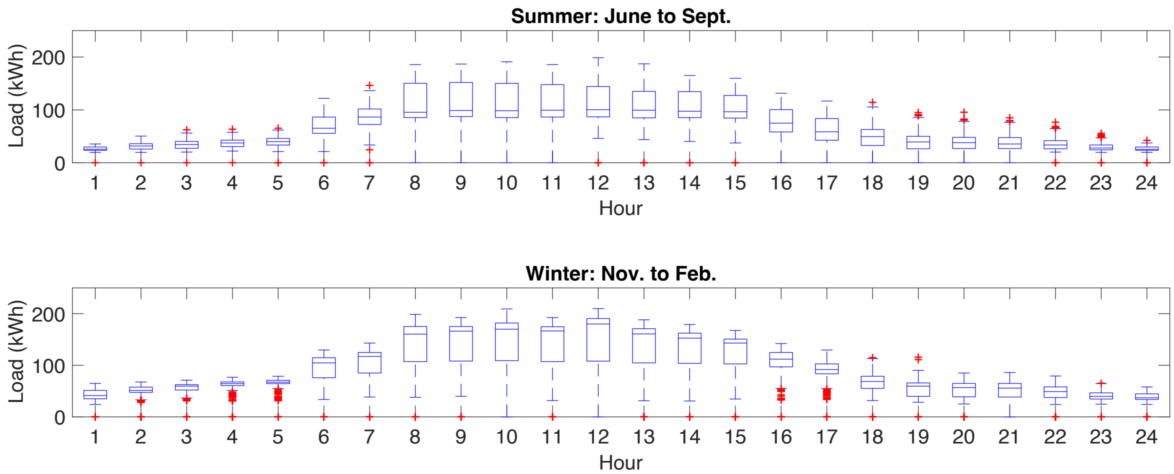

Figure 5.2. Seasonal boxplot of hourly electricity load at Miller Junior High School

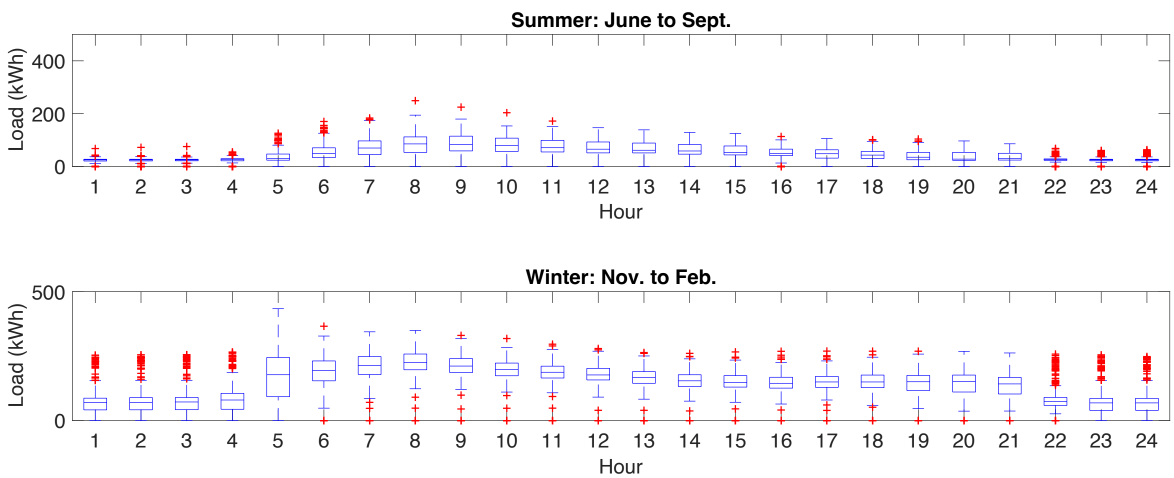

Figure 5.3. Seasonal boxplot of hourly electricity load at Hoquiam Middle School

5.5 Electricity Rates

5.5.1 Existing Flat Rate

GHPUD provides electricity to all three selected schools under the Large General Service Rate (Schedule 55, 2023), which is applicable to customers with a demand of 50 kW or greater and served at 600 volts or less. The monthly electricity charges are the sum of the customer charge, energy charge, and demand charge, and are subject to a minimum charge threshold:

1) Customer Charge: $32.71 per month;

2) Energy Charge: $0.0605 per kWh;

3) Demand Charge: $12.03 per kW per month;

4) Minimum Charge: $87.63 per month, or $1.74 per month per kW of system capacity provided by the District to serve customer requirements, whichever is greater.

The use of flexible load and energy storage is mainly for peak demand reduction, and energy shifting does not lead to energy charge reduction under a flat energy charge rate.

5.5.2 Assumed Time-of-Use Rate

The TOU rate schedules are designed to incentivize customers to shift energy consumption to off-peak hours. By offering different electricity rates based on the time of day, TOU rates encourage customers to reduce their energy consumption during peak hours when electricity costs are higher and increase consumption during off-peak hours when rates are lower. Customers can take advantage of lower rates during off-peak hours to perform energy-intensive tasks or charge energy storage, which can then be discharged to reduce the net load during peak hours.

GHPUD currently does not offer any TOU rate schedules. To better understand the benefits of various GEB design options, Pacific Power's Washington Commercial TOU rate (Schedule 29, 2023) was considered in this study. The assessments using a TOU rate not only enhance our understanding of GEB benefits but also offer valuable information that could assist GHPUD in designing their own tariffs to promote electrification and more effectively manage demand.

In Pacific Power's commercial TOU rate, the on-peak hours are defined as:

- From June through September: 2–10 p.m. every day.
- From October through May: 6–8 a.m. and 2–10 p.m. every day.

The remaining hours are off-peak hours. The energy charge rates are:

1) 20.819 ¢/kWh for the first 50 kWh (during on-peak hours);
2) 9.347 ¢/kWh for all additional kWh (during on-peak hours);
3) −1.866 ¢/kWh credit for all off-peak hours.

5.6 Demand Response Program

While no DR programs are currently offered by GHPUD, Idaho Power's Flex Peak Program (Idaho Power, 2023) was adapted and customized in this analysis. This DR program offers cash incentives to commercial and industrial customers who reduce their electric load when called by utilities in summer months. The exact DR start and end dates, time window, notification time in advance, and incentive rates may be updated periodically, although the DR structure remains the same. In 2022, Idaho Power's Flex Peak operated from June 15 to September 15. At a minimum, three events will occur during the season from 2 to 8 p.m., Monday through Friday. Events last between 2 and 4 hours, and customers are notified 2 hours before each event. Incentive payments consist of a fixed payment and a variable payment. The fixed payment was $3.25 per kW per week. Customers are paid this amount even for weeks when an event is not called, up to their nominated amount. For weeks when an event is called, customers receive a $3.25 payment based on the amount of actual kW reduction achieved during the event. The variable payment was $0.2 per kWh. This amount is only provided after the first four events of the season and is based on the amount of kW reduced during the event, multiplied by the length of the event in hours.

In this study, Flex Peak program was modified to better align with the load pattern and potential needs in GHPUD's service territory. While Flex Peak primarily targets summer peaks, GHPUD is more concerned with managing peaks during the winter season. By tailoring Flex Peak's policies to target winter peaks specifically, we can develop a realistic scenario that closely resembles a DR program GHPUD could offer. The corresponding assessments can more realistically capture the potential incentives that the three schools could receive from GHPUD, providing them valuable insights.

The revised DR program is assumed to run from November 1 to February 28, approximately 17 weeks. Similar to Flex Peak, a minimum of three events are assumed to occur from 8 a.m. to 12 p.m., Monday through Friday. The fixed payment structure was informed by GHPUD's 2022 Integrated Resource Plan (Grays Harbor PUD, 2022), which estimates the deferred investment in generation capacity at $103 per kW per year. This estimate serves as a benchmark for the incentives that GHPUD may offer to customers. Accordingly, the DR fixed payment is set at $103 per kW annually, translating to $6.06 per kW per week over the 17-week program period. The remaining policies are assumed to be the same as the Flex Peak Program.

5.7 Gas Heating Load

Both Central Elementary and Miller Junior High School are currently equipped with gas boilers. Gas heating load is required to determine the existing natural gas energy costs and estimate the electrified heating load in the Intermediate and Advanced designs. In this study, we only collected the 2019 monthly gas consumption (in therms) at Miller Junior High School. Therefore, the procedures outlined in Section 4.2 were used for gas and electric heating load estimation, where EnergyPlus was used for simulating the two school buildings.

- Miller Junior High School covers an area of 88,000 square feet, while the area of DOE's typical secondary school building model is 210,886 square feet. To estimate the heating load of Miller Junior High School, the supply-side gas heating load of the typical primary school building was first simulated using EnergyPlus and then scaled by a factor of 0.42 (88,000/210,886). Based on the school's total gas consumption in 2019, we further scaled the simulated supply-side gas heating load by a coefficient of 2.5 to estimate the actual gas heating load, as plotted in Figure 5.4. Note that the heating load during the summer season (from June to September) was nonzero from EnergyPlus because of reheating processes, but it was set to zero in this study as there was no reheating applied to Miller Junior High School during this period. As can be seen, the estimated peak gas heating load is about 350 kW, occurring in January. The estimated annual gas consumption at Miller Junior High is about 32,713 therms.

- Central Elementary covers an area of 35,000 square feet, while the area of DOE's typical primary school building model is 73,960 square feet. To estimate the heating load of Central Elementary, the supply-side gas heating load of the typical primary school building was first simulated using EnergyPlus and then scaled by a factor of 0.47 (35,000/73,960). The same scaling coefficient as Miller Junior High School was applied here to estimate the actual gas heating load for Central Elementary, which is plotted in Figure 5.5. The summer heating load was also set to zero for the same reason as Miller Junior High School. As can be seen, the estimated peak gas heating load at Central Elementary is around 180 kW, occurring in January, whereas the school's estimated annual gas consumption is about 13,010 therms.

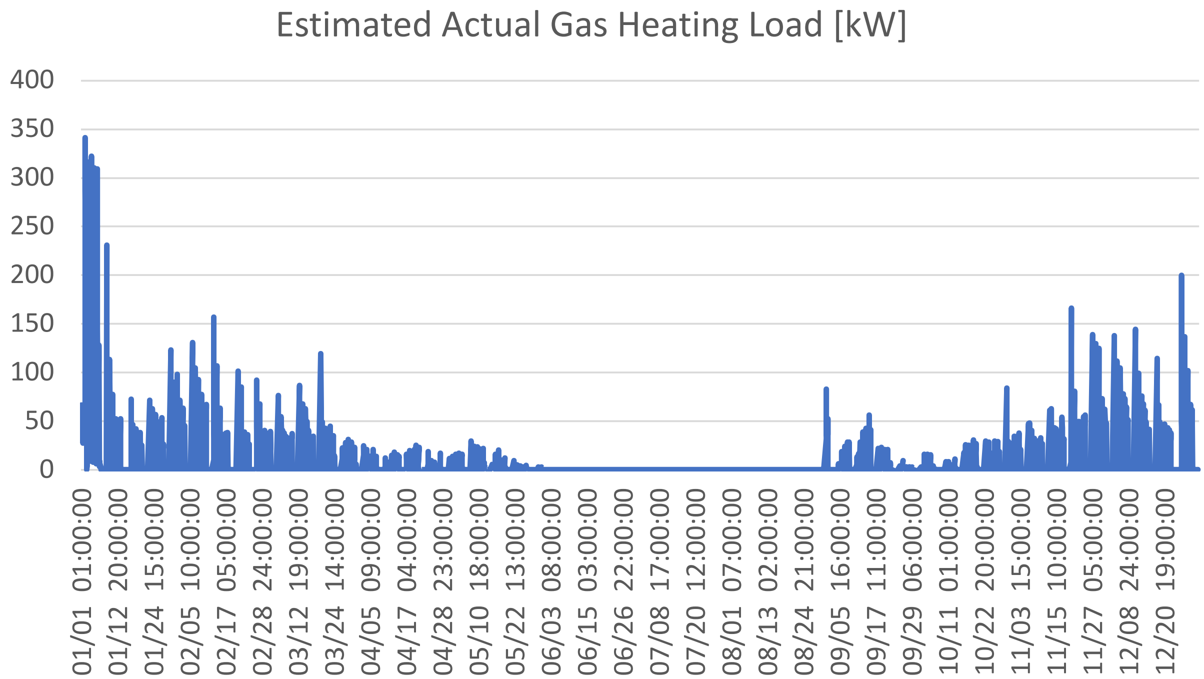

Figure 5.4. Estimated actual gas heating load at Miller Junior High School

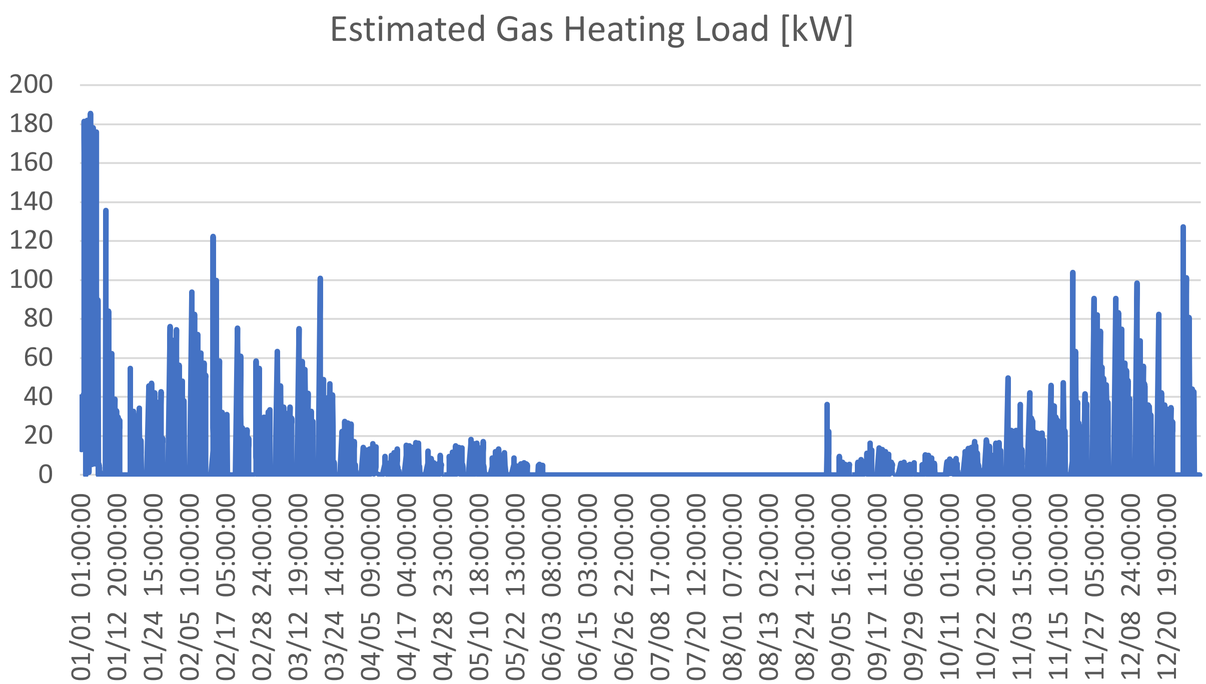

Figure 5.5. Estimated actual gas heating load at Central Elementary

This study also assumes that electric heating is 15% more efficient than gas heating. Hence, we applied a scaling coefficient of 0.85 to both schools' estimated gas heating load, converting the gas heating load into electric heating load.

5.8 Natural Gas Rate

Cascade Natural Gas Corporation is the provider of natural gas service for the Aberdeen School District. The natural gas energy charges for Central Elementary and Miller Junior High School are calculated based on the General Commercial Service Rate (Schedule 504, 2023). The charges comprise a basic service fee, a delivery charge, and the cost of the natural gas. The latter two are calculated based on the volume of gas consumed, measured in therms, where one therm equals 100,000 British thermal units. The three components are listed as follows:

1) Basic Service Charge: $13.00 per month;
2) Delivery Charge: $0.28432 all therms per month;
3) Natural Gas Costs: $0.72936 all therms per month.

CHAPTER 6

Assessment Results

In this study, the Energy Storage Evaluation Tool developed at PNNL was customized and used for techno-economic assessments over a time horizon of 20 years with a discount rate of 6.8%. The inflation rate for both energy and annual O&M costs is assumed to be 5%. The first three sections of this chapter detail the assessment results for each school, while the last section discusses GHPUD's benefits. The results for each school are organized into three parts: the first focuses on results using current electricity rates; the second examines results under a TOU rate; and the third provides a present value analysis and compare the net present value (NPV) costs of different GEB design options.

6.1 Central Elementary

6.1.1 Flat Electricity Rate

Table 6.1 summarizes the annual energy costs and DR benefits under the existing flat rate tariff by design option. Key findings and insights for each design option are offered as follows.

Table 6.1. Central Elementary's Annual Energy Costs and DR Benefits with Flat Rate

Central Elementary								
GEB Design Options		Annual Operational Costs					DR Incentive	Net Benefits
		Gas	Electricity (Flat Rate)		Total	Increased Costs		
			Energy	Demand				
Basic		$13,345	$12,802	$7,813	$33,960	NA	NA	NA
Intermediate	0% LF	NA	$32,806	$20,625	$53,431	$19,471	NA	-$19,471
	30% LF	NA	$32,958	$14,836	$47,795	$13,835	$1,642	-$12,193
	30% LF + BESS	NA	$33,369	$12,129	$45,498	$11,539	$17,157	$5,618
Advanced	30% LF + BESS + TES	NA	$30,664	$10,857	$41,521	$7,561	$20,651	$13,090

- In the Basic GEB design for Central Elementary, the old gas boilers are replaced by new efficient boilers for heating. The estimated annual natural gas consumption is 13,010 therms, and the corresponding natural gas cost is $13,345. On the other hand, the school's annual electricity consumption is around 205 MWh, with an average monthly peak of 54 kW. The corresponding energy and demand charges are $12,802 and $7,813, respectively. The total annual gas and electricity cost at Central Elementary with the Basic design is $33,960.

- In the Intermediate GEB design, the gas boilers are replaced by electric boilers and heat pumps. Such electrification will increase the annual electricity consumption from 210 to 536 MWh, with an average monthly peak of 143 kW.
  - Without advanced controls to utilize any LF, the annual energy charge and demand charge are $32,806 and $20,625, respectively. The total annual energy cost is $53,431, which is $19,471 higher than the Basic design.
  - With 30% LF, the annual energy and demand charges are $32,958 and $14,836, respectively. The corresponding total annual energy cost is $47,795, which is reduced by 11% compared to the case with 0% LF. DR benefit is estimated at $1,642.
  - Lastly, with a 200 kW/600 kWh BESS integrated into the Intermediate design, the average monthly peak demand can be reduced to 84 kW, corresponding to a demand charge of $12,129. Even with a slight increase in energy charge, the school's annual energy cost is still reduced by over $2,000 compared to the case without BESS. Moreover, adding BESS leads to an additional DR benefit of $17,157.

- In the Advanced GEB design, the combination of BESS and TES can further reduce the monthly peak demand by 11%. Figure 6.1 compares the monthly peak with and without demand-side flexibility from load and energy storage. It was found that the school's average monthly peak is reduced from 126 kW to 75 kW. There is also an additional 10% reduction in energy charge and a 20% increase in DR benefit.

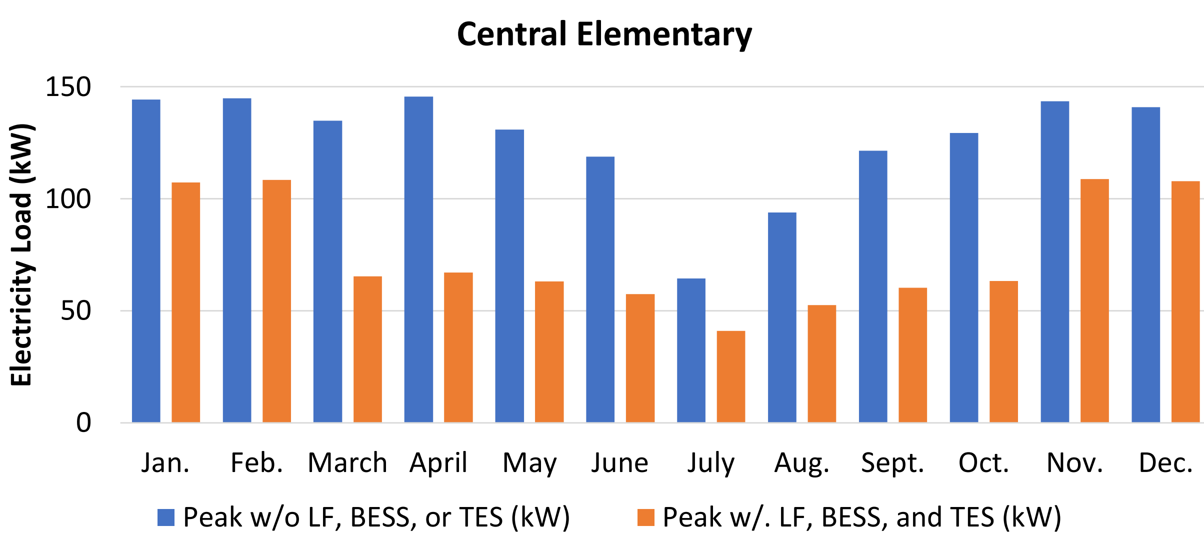

Figure 6.1. Central Elementary's monthly peaks

6.1.2 TOU Electricity Rate

Table 6.2 summarizes the annual energy costs and DR benefits under the assumed TOU rate tariff by design option. Key findings and insights for each design option are offered as follows.

Table 6.2. Central Elementary's Annual Energy Costs and DR Benefits with TOU Rate

Central Elementary								
GEB Design Options		Annual Operational Costs				DR Incentive	Net Benefits
		Gas	Electricity (TOU Rate)	Total	Increased Costs		
Basic		$13,345	$18,151	$31,496	NA	NA	NA
Intermediate	0% LF	NA	$45,285	$45,285	$13,789	NA	-$13,789
	30% LF	NA	$45,698	$45,698	$14,202	$1,642	-$12,560
	30% LF + BESS	NA	$44,088	$44,088	$12,592	$17,277	$4,685
Advanced	30% LF + BESS + TES	NA	$41,784	$41,784	$10,288	$20,738	$10,450

- For the Basic design, the school's annual electricity bill is reduced from $20,615 with the flat rate to $18,151 with the assumed TOU rate.
- With complete electrification in the Intermediate design, LF and energy storage do not significantly affect the annual energy cost under the TOU rate without any demand charge. Most of the benefits come from DR.
- The operational net benefits with the Advanced GEB design are about twice of those with the Intermediate design with BESS.

6.1.3 Present Value Analysis

The present value costs and benefits for different GEB design options are compared in Figure 6.2, with key findings summarized as follows.

- For the Basic design, the present value cost (GEB upgrade cost plus energy cost) is approximately $2.2 million. With the TOU rate, the present value costs can be reduced by about 4% to $2.1 million compared to the flat rate. The Basic GEB design yields the lowest NPV cost.
- The NPV cost of the Intermediate design is $4.5 million. Besides raising the capital cost by 50%, the complete electrification of the HVAC system also increases electricity cost by about 50%. LF does not help reduce energy cost under the TOU rate.
- A 200 kW/600 kWh BESS and microgrid capability increase the capital cost by $433,840, while the present value benefits from energy cost reduction, DR, and outage mitigation are approximately $0.9 million. Therefore, the NPV cost is reduced by about $0.5 million.
- The present value cost of the Advanced design option is about $6.1 million. Considering the incentives from BPA, as well as benefits of carbon reduction, outage mitigation, and DR, the

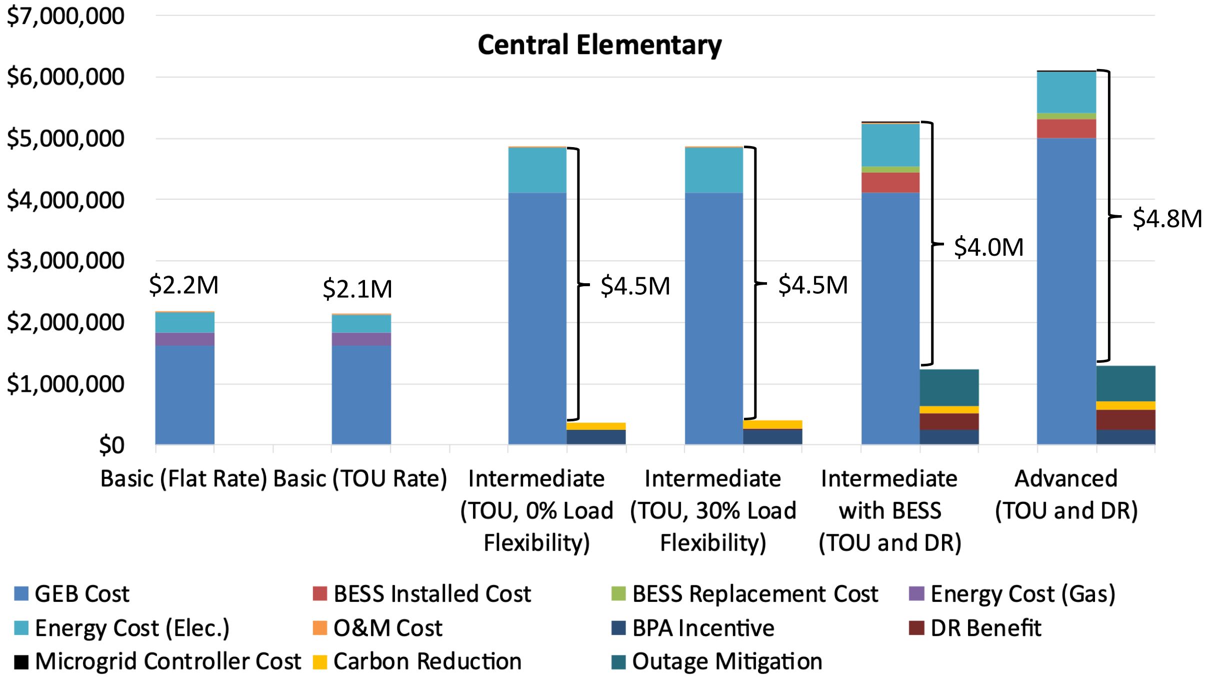

Figure 6.2. Present value costs and benefits for Central Elementary

NPV cost is $4.8 million. While the Advanced design option aims to achieve a low carbon footprint and efficient grid interactivity, it requires a broader array of incentives to fully embrace this option.

6.2 Miller Junior High School

6.2.1 Flat Electricity Rate

Table 6.3 summarizes the annual energy costs and DR benefits under the existing flat rate tariff by design option. Key findings and insights for each design option are offered as follows.

- In the Basic GEB design for Miller Junior High School, the old gas boilers are replaced by new efficient boilers for heating. The estimated annual natural gas consumption is 32,713 therms, and the corresponding natural gas cost is $33,317. On the other hand, the school's annual electricity consumption is around 578 MWh, with an average monthly peak of 172 kW. The corresponding energy and demand charges are $35,354 and $24,800, respectively. The total annual gas and electricity cost at Miller Junior High School with the Basic design is $93,470.

- In the Intermediate GEB design, the gas boilers are replaced by electric boilers and heat pumps. Such electrification will increase the annual electricity consumption from 578 to 1406 MWh, with an average monthly peak demand of 422 kW.
  - Without any advanced controls for energy shifting, the annual energy charge and demand charge are $85,441 and $60,941, respectively. The total annual energy cost is $146,382, which is $52,912 higher than the Basic design.

- With 30% LF, the annual energy and demand charges are $86,118 and $43,537, respectively. The corresponding total annual energy cost is $129,654, which is reduced by 11% compared to the previous case. The LF also results in an increased DR capability, generating an additional DR benefit of $7,143.
- Lastly, with a 500 kW/1500 kWh BESS integrated into the Intermediate design, the average monthly peak demand can be reduced to 242 kW. Although the energy charge increases slightly, the annual energy cost can still be reduced by more than $7,000. Moreover, an additional $45,963 can be received from DR, reducing the annual energy cost by about $16,970 compared to the Basic design.

- In the Advanced GEB design, the combination of BESS and TES can reduce the peak demand by over 40% compared to the Basic design. Figure 6.3 compares the monthly peak with and without demand-side flexibility from load and energy storage. It was found that the school's average monthly peak can be reduced from 372 kW to 211 kW. The energy charge can be also reduced to $79,827. With an additional DR benefit of $55,594, the school's annual energy cost is $38,807 lower than the Basic design.

Table 6.3. Miller Junior High School's Annual Energy Costs and DR Benefits with Flat Rate

Miller Junior High School								
GEB Design Options		Annual Operational Costs					DR Incentive	Net Benefits
		Gas	Electricity (Flat Rate)		Total	Increased Costs		
			Energy	Demand				
Basic		$33,317	$35,354	$24,800	$93,470	NA	NA	NA
Intermediate	0% LF	NA	$85,441	$60,941	$146,382	$52,912	NA	-$52,912
	30% LF	NA	$86,118	$43,537	$129,654	$36,184	$7,143	-$29,042
	30% LF + BESS	NA	$87,508	$34,954	$122,463	$28,993	$45,963	$16,970
Advanced	30% LF + BESS + TES	NA	$79,827	$30,430	$110,257	$16,787	$55,594	$38,807

6.2.2 TOU Electricity Rate

Table 6.4 summarizes the annual energy costs and DR benefits under the assumed TOU rate tariff by design option, with key findings provided as follows.

- For the Basic design, the school's annual electricity bill is reduced from $93,470 with the flat rate to $81,771 with the assumed TOU rate.

- With complete electrification in the Intermediate design, the school's annual energy costs are $115,964 and $117,637 with 0% and 30% LF, respectively. With BESS incorporated into the Intermediate GEB design, the school can receive annual cost savings of $14,194 compared to the Basic design.

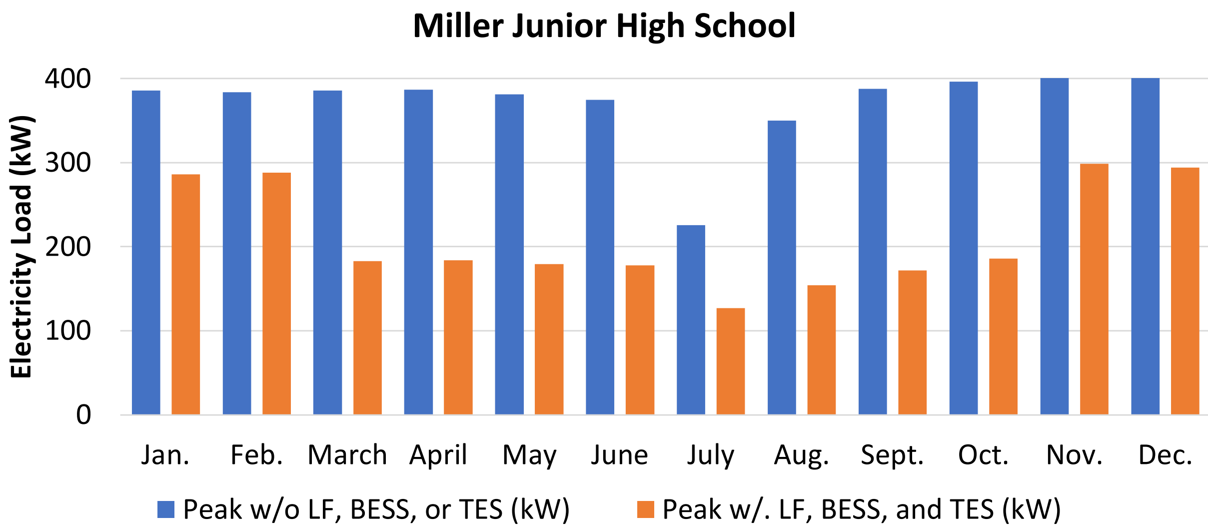

Figure 6.3. Miller Junior High School's monthly peaks

- The Advanced GEB design boosts the annual cost savings to $29,597.

Table 6.4. Miller Junior High School's Annual Energy Costs and DR Benefits with TOU Rate

Miller Junior High School								
GEB Design Options		Annual Operational Costs					DR Incentive	Net Benefits
		Gas	Electricity (TOU Rate)	Total	Increased Costs			
Basic		$33,317	$48,454	$81,771	NA		NA	NA
Intermediate	0% LF	NA	$115,964	$115,964	$34,193		NA	-$34,193
	30% LF	NA	$117,637	$117,637	$35,866		$7,143	-$28,723
	30% LF + BESS	NA	$113,807	$113,807	$32,036		$46,230	$14,194
Advanced	30% LF + BESS + TES	NA	$107,924	$107,924	$26,153		$55,750	$29,597

6.2.3 Present Value Analysis

The present value costs and benefits for different GEB design options are compared in Figure 6.4, with key findings summarized as follows.

- For the Basic design, the present value costs with the flat and TOU rates are $3.9 million and $3.7 million, respectively.

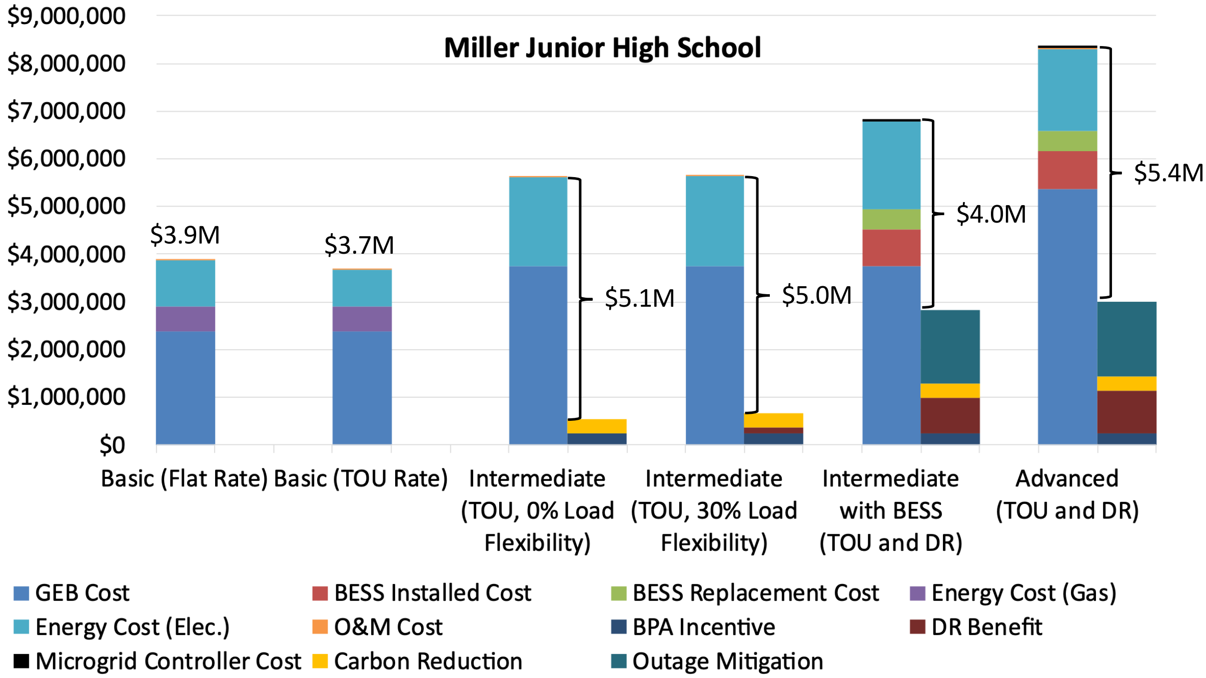

Figure 6.4. Present value costs and benefits for Miller Junior High School

- The NPV cost associated with the Intermediate design is approximately $5.1 million. Due to the complete electrification of the school's HVAC system, the associated GEB design and energy costs increase by 58% and 42%, respectively.
- A 500 kW/1500 kWh BESS and microgrid capability increase the capital cost by $1.2 million, while the present value benefits from energy cost reduction, DR, and outage mitigation are approximately $2.2 million. Therefore, the NPV cost is reduced by about $1 million.
- The present value cost of the Advanced design option is about $8.2 million. Considering the incentives from BPA, as well as benefits of carbon reduction, outage mitigation, and DR, the NPV cost is $5.4 million.

6.3 Hoquiam Middle School

6.3.1 Flat Electricity Rate

Table 6.5 summarizes the annual energy costs and DR benefits under the existing flat rate tariff by design option. Key findings and insights for each design option are offered as follows.

- In the Basic GEB design, Hoquiam Middle School is fully electrified. The school's annual electricity consumption is 749 MWh, with an average monthly peak of 218 kW. The corresponding electricity energy and demand charges are $45,719 and $31,481, respectively. The total annual electricity cost at Hoquiam Middle School is $77,200.
- In the Intermediate GEB design, the control system will be upgraded. Such an upgrade and optimization reduce the annual electricity consumption from 749 to 708 MWh, with an average monthly peak of 206 kW.

- With 0% LF, the annual energy charge and demand charge are $43,201 and $29,732, respectively. The total annual energy cost is $72,933, which is $4,267 lower than the Basic design.
- With 30% LF, the annual energy and demand charges are $43,309 and $21,070, respectively. The corresponding total annual energy cost is $64,379, which is reduced by 12% compared to the previous case.
- Lastly, with a 400 kW/1200 kWh BESS integrated into the Intermediate design, the average monthly peak demand can be reduced to 137 kW. Although the energy charge increases slightly, the school's annual energy cost is reduced to $63,679. Moreover, an additional $31,177 can be received for DR, reducing the school's annual energy cost by about $44,698 compared to the Basic design.

- In the Advanced GEB design, the combination of BESS and TES reduces the peak demand by about 37% compared to the Basic design. Figure 6.5 compares the monthly peak with and without demand-side flexibility from load and energy storage. It was found that the school's average monthly peak can be reduced from 182 kW to 117 kW. The energy charge is reduced to $40,884 and DR benefits increase to $36,547. The school's annual energy cost is $55,942 lower than the Basic design.

Table 6.5. Hoquiam Middle School's Annual Energy Costs and DR Benefits with Flat Rate

Hoquiam Middle School								
GEB Design Options		Annual Operational Costs					DR Incentive	Net Benefits
		Gas	Electricity (Flat Rate)		Total	Increased Costs		
			Energy	Demand				
Basic		NA	$45,719	$31,481	$77,200	NA	NA	NA
Intermediate	0% LF	NA	$43,201	$29,732	$72,933	-$4,267	NA	$4,267
	30% LF	NA	$43,309	$21,070	$64,379	-$12,821	$578	$13,399
	30% LF + BESS	NA	$43,860	$19,819	$63,679	-$13,521	$31,177	$44,698
Advanced	30% LF + BESS + TES	NA	$40,884	$16,921	$57,805	-$19,395	$36,547	$55,942

6.3.2 TOU Electricity Rate

Table 6.6 summarizes the annual energy costs and DR benefits under the assumed TOU rate tariff by design option. Key findings and insights for each design option are offered as follows.

- For the Basic design, the school's annual electricity cost is reduced from $77,200 with the flat rate to $62,897 with the assumed TOU rate.

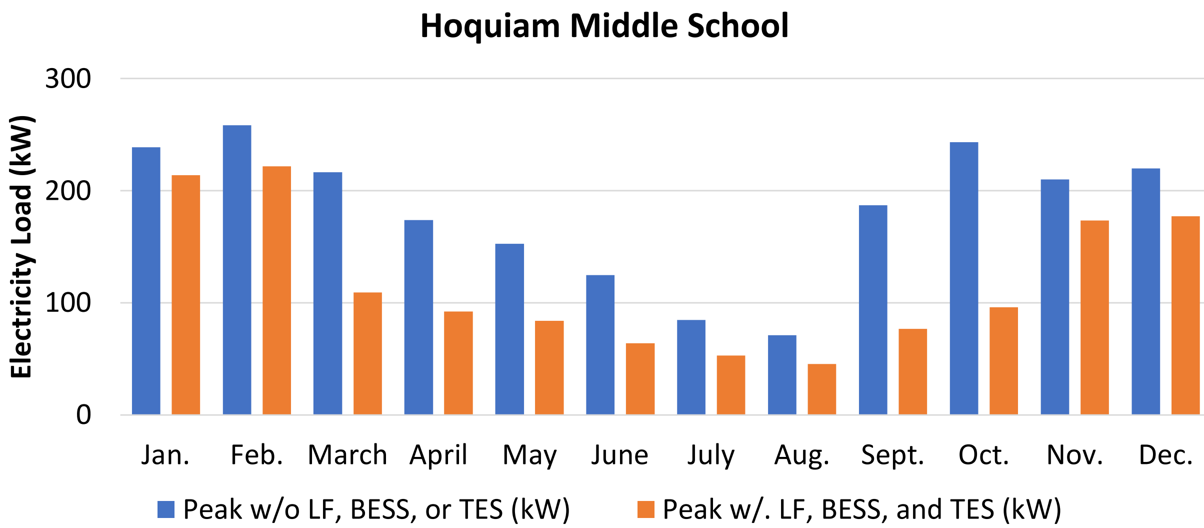

Figure 6.5. Hoquiam Middle School's monthly peaks

- In the Intermediate design, the school's annual energy costs are \$59,476 and \$59,661 with 0% and 30% LF, respectively. With BESS incorporated into the Intermediate GEB design, the school can receive annual cost savings of \$37,094 compared to the Basic design.
- The Advanced GEB design boosts the annual cost savings to \$44,570.

Table 6.6. Hoquiam Middle School's Annual Energy Costs and DR Benefits with TOU Rate

Hoquiam Middle School								
GEB Design Options		Annual Operational Costs				DR Incentive	Net Benefits
		Gas	Electricity (TOU Rate)	Total	Increased Costs		
Basic		NA	$62,897	$62,897	NA	NA	NA
Intermediate	0% LF	NA	$59,476	$59,476	-$3,422	NA	$3,422
	30% LF	NA	$59,661	$59,661	-$3,236	$578	$3,814
	30% LF + BESS	NA	$57,650	$57,650	-$5,247	$31,847	$37,094
Advanced	30% LF + BESS + TES	NA	$55,141	$55,141	-$7,756	$36,814	$44,570

6.3.3 Present Value Analysis

The present value costs and benefits for different GEB design options are compared in Figure 6.6, with key findings summarized as follows.

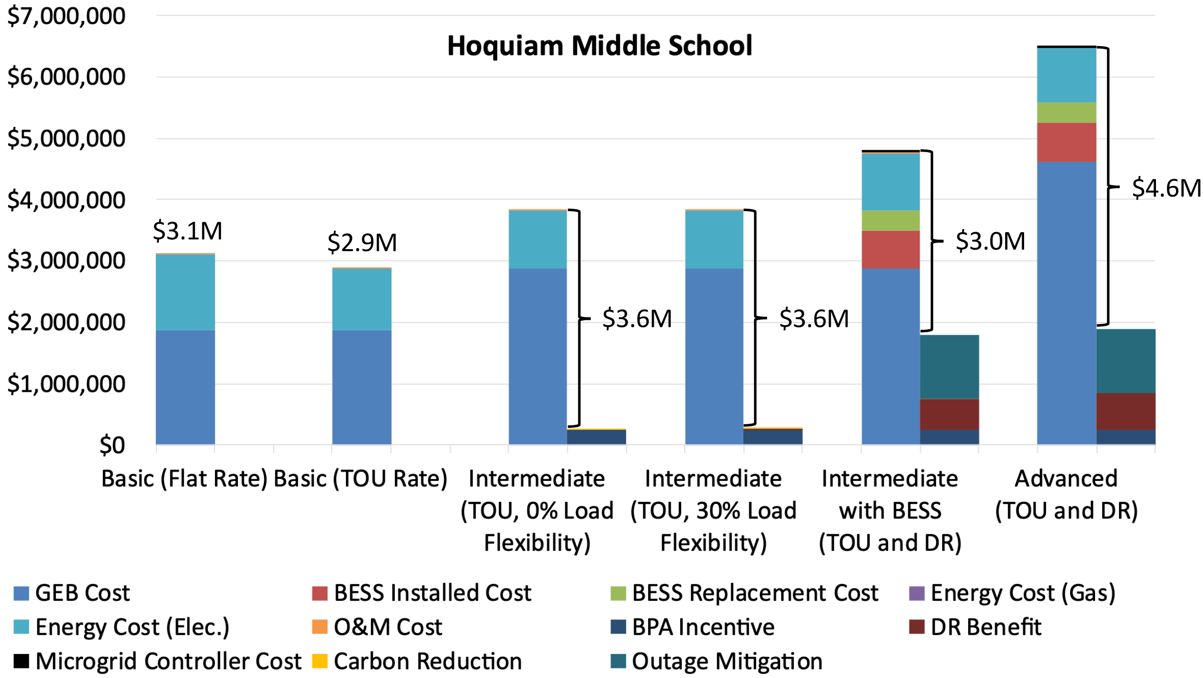

Figure 6.6. Present value costs and benefits for Hoquiam Middle School

- For the Basic design, the present value costs with the flat and TOU rates are $3.1 million and $2.9 million, respectively.
- The NPV cost associated with the Intermediate design is approximately $3.6 million. Specifically, the associated GEB update cost increases by 53% compared to the Basic design, while the present value energy cost decreases by 5%.
- A 400 kW/1200 kWh BESS and microgrid capability increase the capital cost by $1 million, while the present value benefits from energy cost reduction, DR, and outage mitigation are approximately $1.6 million. Therefore, the NPV cost is reduced by about $0.6 million, making this design option the most economically attractive.
- The present value cost of the Advanced design option is about $6.5 million. Considering the incentives from BPA, as well as benefits of carbon reduction, outage mitigation, and DR, the NPV cost is $4.6 million.

6.4 GHPUD Benefits

By embracing the Advanced GEB design option and incorporating featured DR programs, all selected schools could collectively contribute to a yearly reduction of 1,080 kW in GHPUD's system peak demand. This reduction in peak demand plays a vital role in enabling GHPUD to circumvent or curtail its reliance on new peaking resources, translating into substantial cost savings on fuel and operational expenditures. Concurrently, it empowers GHPUD to reinforce grid reliability while postponing substantial investments in infrastructure upgrades. The act of lowering peak demand also resonates with the sustainability objectives of GHPUD—reduced resource consumption, diminished greenhouse gas emissions, and a mitigated environmental footprint.

CHAPTER 7

Conclusions

This report presented techno-economic assessments for various GEB design alternatives for the three schools served by GHPUD: Central Elementary, Miller Junior High School, and Hoquiam Middle School. Utilizing advanced modeling and optimization methods, comprehensive assessments were performed to define technically achievable benefits and determine cost-effectiveness for each GEB design option, considering the operational capabilities and characteristics, applicable use cases, and various system- and component-level constraints.

It should be noted that the equipment and building system technologies considered in this study have significant overlaps with other areas of focus in the broad discussion of electrification that is currently underway in Washington and the nation in general. Buildings using the options of battery and thermal energy storage in the Advanced scenario of this study lend themselves to be included in plans for microgrids. A microgrid is typically defined as a small network of electricity users that take advantage of a localized supply of electricity, allowing the network to detach from the centralized power grid and function independently. With microgrid capabilities, the schools can maintain essential services like lighting and HVAC systems during power outages, ensuring not only an uninterrupted learning environment but also enhanced safety and health conditions for students and staff. Additionally, the school's microgrid capability positions it as a potential emergency shelter for the community, providing a reliable source of power and essential services during widespread outages. The larger the building, the more potential value for resilience, particularly if it can provide a certain level of electrical service while disconnected from the utility grid.

Utilizing a combination of the options discussed in this study also benefits utilities. The deferral of costs for upgrading substation, transmission, and distribution assets can be substantial. In general, the larger the building converted to GEB, the greater the cost savings in terms of equipment upgrades for the utility. Furthermore, utilities may avoid or delay the need to construct additional power generation facilities or acquire extra resources from the open market, resulting in significant cost savings.

Energy storage plays a vital role in firming renewable generation and enhancing grid reliability. Battery energy storage is increasingly being recognized globally as a powerful solution to energy independence and security, sustainable development, and carbon emission reduction. Battery and thermal energy storage also offer additional benefits, such as energy shifting which results in reduced energy charges from utilities, peak demand reduction, and demand side management. On the other hand, these use cases can also benefit utilities by lowering their operational costs, meeting resource adequacy, deferring infrastructure investments, and contributing to environmental sustainability. Communities that employ a thoughtful approach to integrating energy storage technologies when electrifying a public building can leverage a variety of public grant funding, rebates from utilities, as well as local, state, and federal tax rebates to help offset the costs associated with the building fuel switch. Discussing the multiple benefits of these technologies with citizens in the area could enhance support by sharing the advantages with a wider cross-section of the public.

CHAPTER 8

References

Balducci, P., J. Alam, T. Hardy, and D. Wu 2018, June. Assigning value to energy storage systems at multiple points in an electrical grid. *Energy & Environmental Science 11*(8), 1926–1944.

Balducci, P., K. Mongird, D. Wu, D. Wang, V. Fotedar, and R. T. Dahowski 2020. An evaluation of the economic and resilience benefits of a microgrid in Northampton, Massachusetts. *Energies 13*. 4802.

Das, A., D. Wu, and Z. Ni 2022, November. Approximate dynamic programming with customized policy design for microgrid online dispatch under uncertainties. *International Journal of Electrical Power & Energy Systems 142*. 108359.

DOE, Office of EERE 2023. Building Energy Codes Program — Prototype Building Models. Available online at <https://www.energycodes.gov/prototype-building-models#Commercial>.

Du, Y. and D. Wu 2022, April. Deep reinforcement learning from demonstrations to assist service restoration in islanded microgrids. *IEEE Transactions on Sustainable Energy 13*(2), 1062–1072.

Electricity Maps 2023. Bonneville Power Administration. Available online at <https://app.electricitymaps.com/zone/US-NW-BPAT>.

EnergyPlus 2023. EnergyPlus version 23.1.0. Available online at <https://energyplus.net/>.

EPA 2023. Power Profiler: Find Your Electricity Emissions. Available online at <https://www.epa.gov/egrid/power-profiler#/>.

Giraldez, J., F. Flores-Espino, S. MacAlpine, and P. Asmus 2018. Phase I microgrid cost study: Data collection and analysis of microgrid costs in the United States. Technical report, National Renewable Energy Laboratory.

Grays Harbor PUD 2022. Integrated Resource Plan. Available online at <https://www.ghpud.org/wp-content/uploads/2022-GHPUD-Inetgrated-Resource-Plan_Final.pdf>.

Grays Harbor PUD 2023. Annual Outage Data. Available online at <https://www.ghpud.org/wp-content/uploads/System-Reliability-May-2023.pdf>.

Hao, H., D. Wu, J. Lian, and T. Yang 2018, September. Optimal coordination of building loads and energy storage for power grid and end user services. *IEEE Transactions on Smart Grid 9*(5), 4335–4345.

Huang, B., S. Huang, X. Ma, S. Katipamula, D. Wu, and R. Lutes 2023, September. Stochastic scheduling for commercial building cooling systems: considering uncertainty in zone temperature prediction. *Applied Energy 346*. 121367.

Huang, S., Y. Ye, D. Wu, and W. Zuo 2021, April. An assessment of power flexibility from commercial buildings in the United States. *Energy*. 119571.

Idaho Power 2023. Flex Peak Demand Response Program. Available online at <https://www.idahopower.com/energy-environment/ways-to-save/savings-for-your-business/flex-peak/>.

Kirchmeier, B. 2018. Clean Energy Funds: 2013–18. Available online at <https://energyleadershipsummit.com/wp-content/uploads/2A_Kirchmeier.pdf>.

Lawrence Berkeley National Laboratory 2018. The Interruption Cost Estimate (ICE) Calculator. Available online at <https://www.icecalculator.com/build-model?model=interruption>.

Ma, K., D. Wang, J. Lian, D. Wu, and S. Katipamula 2020, October. Market-based co-optimization of energy and ancillary services with distributed energy resource flexibilities. In *Proceedings of the IEEE Power and Energy Society Transmission and Distribution Conference and Exposition*, pp. 1–5.

Ma, X., D. Wu, and A. Crawford 2022. Energy Northwest Horn Rapids solar and storage: A techno-economic assessment. Technical report, Pacific Northwest National Laboratory.

Pacific Northwest National Laborotary 2023. Energy Storage Cost and Performance Database. Available online at <https://www.pnnl.gov/ESGC-cost-performance>.

Schedule 29 2023. Pacific Power's Washington Commercial Time-of-Use Rate. Available online at <https://www.pacificpower.net/savings-energy-choices/time-of-use.html>.

Schedule 504 2023. Cascade Natural Gas' General Commercial Service Rate. Available online at <https://www.cngc.com/rates-services/rates-tariffs/#washington>.

Schedule 55 2023. Grays Harbor PUD's Large General Service Rate. Available online at <https://www.ghpud.org/customer-service/customer-rates-fees/>.

Wang, J., S. Huang, D. Wu, and N. Lu 2021, January. Operating a commercial building HVAC load as a virtual battery through airflow control. *IEEE Transactions on Sustainable Energy 12*(1), 158–168.

Washington Policy Center 2023. Cost of Washington's CO_2 Tax Jumps to 45 Cents per Gallon. Available online at <https://www.washingtonpolicy.org/publications/detail/cost-of-washingtons-co2-tax-jumps-to-45-cents-per-gallon#:~:text=The%20Washington%20State%20Department%20of,cents%20per%20gallon%20for%20diesel.>.

Washington State Department of Commerce 2017. Clean Energy Fund. Available online at <http://www.commerce.wa.gov/wp-content/uploads/2017/04/Commerce-Clean-Energy-Fund-2017.pdf>.

Washington State Department of Commerce 2023. Grid Modernization Program. Available online at <https://www.commerce.wa.gov/growing-the-economy/energy/clean-energy-fund/energy-grid-modernization/>.

Wu, D., H. Hao, T. Fu, and K. Kalsi 2018, April. Regional assessment of virtual battery potential from building loads. In *Proceedings of the IEEE Power and Energy Society Transmission and Distribution Conference and Exposition*, pp. 1–5.

Wu, D., R. Hu, X. Ma, S. Huang, B. Huang, K. Oikonomou, C. K. Vartanian, and M. Diedesch 2022. Avista's shared energy economy model pilot–a techno-economic assessment. Technical Report PNNL-33107, Pacific Northwest National Laboratory.

Wu, D., C. Jin, P. Balducci, and M. Kintner-Meyer 2015, July. An energy storage assessment: Using optimal control strategies to capture multiple services. In *Proceedings of the IEEE Power and Energy Society General Meeting*, Denver, CO, pp. 1–5.

Wu, D., M. Kintner-Meyer, T. Yang, and P. Balducci 2016, July. Economic analysis and optimal sizing for behind-the-meter battery storage. In *Proceedings of the IEEE Power and Energy Society General Meeting*, Boston, MA, pp. 1–5.

Wu, D., M. Kintner-Meyer, T. Yang, and P. Balducci 2017, August. Analytical sizing methods for behind-the-meter battery storage. *Journal of Energy Storage 12*, 297–304.

Wu, D., J. Lian, Y. Sun, T. Yang, and J. Hansen 2017, September. Hierarchical control framework for integrated coordination between distributed energy resources and demand response. *Electric Power Systems Research 150*, 45–54.

Wu, D. and X. Ma 2021. Modeling and optimization methods for controlling and sizing grid-connected energy storage: A review. *Current Sustainable/Renewable Energy Reports 8*, 123–130.

Wu, D., X. Ma, P. Balducci, and D. Bhatnagar 2021, March. An economic assessment of behind-the-meter photovoltaics paired with batteries on the Hawaiian Islands. *Applied Energy 286*. 116550.

Wu, D., X. Ma, T. Fu, Z. Hou, P. Rehm, and N. Lu 2022, August. Design of a battery energy management system for capacity charge reduction. *9*, 351–360.

Wu, D., X. Ma, S. Huang, T. Fu, and P. Balducci 2020, May. Stochastic optimal sizing of distributed energy resources for a cost-effective and resilient microgrid. *Energy 198*. 117284.

Wu, D., P. Wang, X. Ma, and K. Kalsi 2020, April. Scheduling and control of flexible building loads for grid services based on a virtual battery model. In *21th IFAC World Congress*, Volume 53, pp. 13333–13338.

Wu, D., T. Yang, A. A. Stoorvogel, and J. Stoustrup 2017, April. Distributed optimal coordination for distributed energy resources in power systems. *IEEE Transactions on Automation Science and Engineering 14*(2), 414–424.

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)

www.pnnl.gov