Modeling High-power Electric Vehicle Impacts within the Swan Island Service Area

Project Report

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Acronyms

BESS Battery Energy Storage System

EV Electric Vehicle

EVCL Electric Vehicle Charging Location

EVSE Electric Vehicle Service Equipment

PCC Point of Common Coupling

PGE Portland General Electric

PSU Portland State University

pu per unit

SOC state-of-charge

ToU Time-of-Use

1 Introduction

The Portland State University (PSU) Power Engineering Group has completed a series of studies to understand the potential impacts of medium-duty Electric Vehicle (EV) charging within the Portland General Electric (PGE) Swan Island distribution system. PGE expects medium-duty EV loading within this service area to grow significantly in coming years; the substation will eventually host numerous Electric Vehicle Charging Locations (EVCLs) where these vehicles will charge. Each of these EVCLs will host one or more Electric Vehicle Service Equipment (EVSE), which themselves range in capacity from small units supporting personal employee vehicles to high-power EVSE charging units for both industrial and commercial fleet use.

PGE expects Swan Island will eventually host eight EVCLs. The PSU team analyzed several of these planned installations. When considering the impact of these EVCLs, both the number of EVs and the different loading characteristics from each charging level were considered over multiple forecast periods. Assets of particular interest were identified for analysis to determine where the system was overloaded by the addition of medium-duty EV charging events. Loading on the two substation transformers was analyzed, as was loading on transformers and conductors near the largest three EVCLs. Feeder conductors between each EVCL and the substation were also analyzed to determine if they presented a possible bottleneck within the distribution system. The team also considered whether EV charging that was incentivized to time-shift by Time-of-Use (ToU) pricing could reduce loading of these assets.

Additionally, the PSU team analysed Battery Energy Storage System (BESS) placement in order to consider how BESS could be used to defer EVSE loading away from peak demand periods as well as reduce customer electricity costs. This analysis considered the power and energy capacities of BESS that would be required to achieve demand curtailment. The team also analyzed how BESS can be used to reduce loading of municipal electric busses operating within a fixed route and using an in-route charger. These analyses show how EVSE loading may be regulated through proper placement and control of BESS.

Key findings: Swan Island has sufficient loading capacity to accommodate most

EVCL load growth scenarios. Swan Island voltages are very stiff, and the substation regulators manage system voltages very well. Load shifts induced by ToU pricing could help alleviate loading by EV charging infrastructure. Co-located BESS can support high penetration medium-duty EV and municipal electric bus adoption by mitigating the need for major distribution system upgrades.

2 Modification of Swan Island CYME Model

This report considers the impacts that medium-duty EV charging could have within the Swan Island electrical distribution system. These impacts include current loading within conductors and transformers, as well as voltage deviations across conductors and at load nodes. These studied highlight the challenges that large-scale medium-duty EV charging could present to PGE's distribution system as industrial EV adoption continues to increase over the coming years.

These studies were conducted within CYMDist using a model of the Swan Island distribution system provided by PGE. CYMDist is the distribution system analysis base package of the CYME software package. CYMDist includes the modeling and analysis tools required to perform electric distribution system simulations.[1]

Figure 1 shows a one-line diagram of the Swan Island substation, which contains two transformers (WR1 and BR1) and five feeders. Two of these feeders (Dolphin and Basin, highlighted) serve the three largest EVCL that are analyzed in this report (WR1-1, WR1-2, and BR2-1).

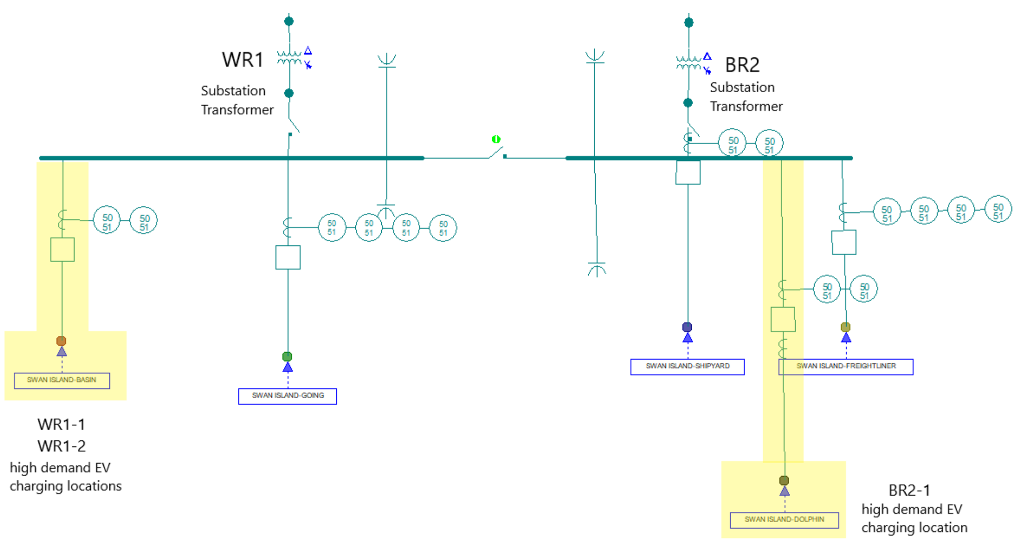

Figure 1: One-line diagram of the Swam Island substation, showing the two substation transformers (WR1 and BR2) and the five feeders. The highlighted feeders, Basin and Dolphin, host the three large EVCL: WR1-1, WR1-2, and BR2-1.

[1] CYMDist Distribution simulation software, www.cyme.com

2.1 Python Tools

The PSU team created a set of data processing and analysis tools for use with EV distribution system impact studies. These tools use Python scripts to interface with, exchange data, and control CYMDist. Other PSU Python tools were used to create the EVCLs loads as well as several BESS models, as needed for several studies. These tools are publicly available within a persistent archive hosted by PDXSholar [1]. Descriptions of these tools, and examples of their use, may be found in the MS Thesis by Sheeran [2]. Appendix A provides descriptions of these python tools and instructions on how to use these tools to conduct studies.

2.2 Load Profiles

Each of the studies conducted for this report span a 24 hour period in order to demonstrate loading impacts though an entire day. The PGE CYME model did not include daily load curve profiles. In order to produce time-varying loads for these studies, the PSU team modified the non-EV load profiles within PGE's CYME model, specifically for the time period of August 15th to the 21st. This range encompasses a high load period. Demand data were selected after finding the hottest average week during the summer within the feeder demand files. This approach did not take into account the demand for individual spot loads, but rather applied a simulated demand modification for each device on the feeders. This simplified load profile was deemed appropriate due to the location of analyzed points focusing on either the EVCLs or the substation transformers.

2.3 Model Error Correction

The PSU team made several error-correction modifications to the PGE Swan Island CYME model, in consultation with PGE, prior to conducting the EV impact studies. Specifically, cable objects with incorrect ratings and by-passed distribution transformers were modified.

Cable rating are assigned via the cable ID properties, which include cable current rating and resistance per mile of line. The PGE CYME model included a number of cable objects with incomplete cable ratings, which were set to a deafault $1A$. With an incorrect rated current of $1A$, any non-zero demand will trigger an overload flag during CYME simulations. These incorrect cable ID properties were changed to use the properties of a *bus bar* object, which has the same loading settings, other than an incorrect $1A$ default rating value.

Within the PGE CYME model, all of the distribution transformers had been bypassed. CYME equipment may be defined using either a single-phase format or dual-phase format, i.e. (AN, BN, CN) or (AB, BC, BA). Transformers placed on dual-phase-rated equipment, but that are only serving single-phase loads, can cause errors during load flow simulations. For example, a transformer supplying AN phase power would need both the AB and CA phases to be also connected to prevent an error message. For this project, all such transformers were reconfigured to correct these errors prior to running CYME simulations.

3 Hosting Capacity: Simulations and Analysis

PGE provided PSU with an EV penetration forecast dataset. The dataset provided projected numbers of medium-duty EVs within the Swan Island Feeder area for every year between 2021 and 2050, and provided three projected levels for each year: low, medium, and high.

PSU used this EV penetration dataset to create EVCL load profiles at five year intervals between 2021 and 2046. These EVCL load profiles consist of medium-duty EV charging events that are informed by the EV penetration forecasts. EVCL demand profiles were created by combining a variety of simulated EV charging events. Profiles were influenced by ranges in EV battery size and initial battery state-of-charge (SOC) (from 25% to 50%). Medium-duty EVs have battery sizes of 80 kW, 100 kW, 160 kW and 200 kW. EVs containing the two larger battery sizes become more common during later forecast years of 2041 and 2046. The first two forecast periods, 2021 and 2026, exclusively contain 80 kW and 100 kW EVs. Larger EV batteries are one of the reasons more asset overloads are observed within the forecast years of 2041 and 2046.

These charging profiles were distributed over a 24 hour period to represent anticipated aggregate medium-duty EV charging profiles. Increases in EVCL profiles were created by placing additional EV charging profiles atop profiles from earlier years. Small segments of EV charging superimposed over each other, which lead to outlying spikes in aggregate demand.

Hosting capacity analyses consider the electrical capacity of cables and transformers within the Swan Island distribution system. Simulations were conducted for each of the six study years at the low, medium, and high projection levels. These hosting capacity simulations account for increases in medium-duty EV penetration with time, but do not consider growth in non-EV demand. The EV impact studies provide a means for assessing potential impacts on specific cables and transformers when planning for EVCL deployment within the Swan Island system.

3.1 Analysis

There are two principle goals when analysing these hosting capacity simulations. For each of the EV penetration cases, the analysis relates EV loading to:

1. the remaining electrical capacities of cables and transformers in order to identify potentially overloaded assets.
2. voltage at loads and across conductors in order to determine nodes that may experience unacceptable voltage deviations.

Analysis of the hosting capacity simulations examine the following:

- Impact on cable loading, specifically cables connected to the three largest EVCLs. Excessive cable loading due to EVSE load growth is compared year-to-year
- Impact on loading and voltage for each of the substation transformers. This shows demand impact across entire Swan Island system, not just the three largest EVCL.
- Impact on undersized cables throughout the Swan Island system, not just the three cables connecting the three largest EVCL to the distribution system.
- Impact on voltages associated with each of the three EVCL transformers. These are the node voltages at the EVCL transformers input.
- Impact on line voltage drop between EVCLs and substation transformers. This compares the output substation voltage with the input voltage of the EVCL transformer.

3.2 EVCL Cable Loading

This study examined loading on cables throughout the Swan Island system. Three in particular are discussed first, in 3.2.1. These connect directly the three heavily-loaded EVCL to distribution transformers. Other cables within the system are also affected by the EVCL, specifically cables located upstream. These are discussed in 3.2.2.

3.2.1 Service Transformer EVCL Cable Loading

This study examined loading on the cables that connect the three heavily-loaded EVCLs to distribution transformers. The 2046 EV load penetration for each of these cables is shown in Table 1. Each of these cables have loading limits that are specified within the Swan Island CYME model. The following plots of cable loading show normalized rated power loading on a percentage scale. The base case Swan Island study shows no instances of overloading on any of these three cables.

Cable ID	***Cable Reference***	***Low***	***Medium***	***High***
PRIUG208435	WR1-1	266	358	465
PRIUG138695	WR1-2	173	234	303
PRIUG228939	BR2-1	105	141	183

Table 1: Cable name references and number of EVs charging at an EVCL each day for the 2046 forecast.

For this study, PSU created distribution transformers for each of the anticipated EVCL, to which these three cables connect. Transformer power ratings are based on the anticipated EV charging profile of the 2046 high penetration EV scenario. These transformers do not represent existing assets within the Swan Island system. Loading on the cables that connect to these transformers serves as a proxy for the anticipated loading on these transformers.

Figure 2 shows the loading on WR1-1, which exceeds the cable rating only briefly in the 2046 high penetration scenario. Though the low penetration plot shows less of an impact than the high penetration plot, there is still a sizable increase in EVCL loading, with a maximum increase of 60% percentage points for the 2046 scenario.

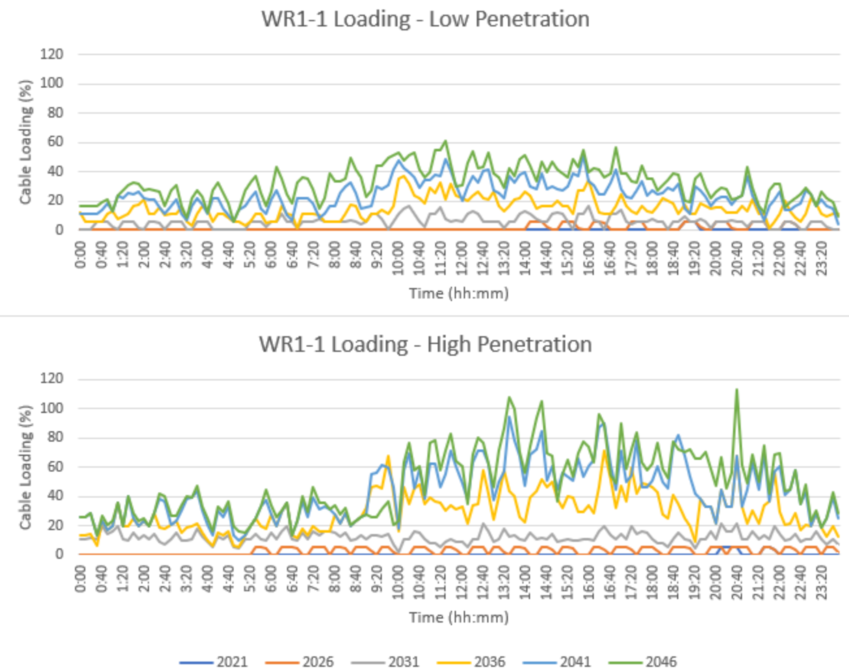

Figure 2: WR1-1 cable loading for low and high EV penetration scenarios over a 24 hour period, 2021-2046.

Figure 3 shows loading within the the second largest EVCL, WR1-2. Unlike WR1-1 and BR2-1, the CYME model included base-case non-EV loading on this cable. WR1-2 is the only EVCL cable analyzed that includes non-EV demand. WR1-2 experiences overloading only briefly in the 2046 high penetration scenario. In this case the EVCL WR1-2 causes a maximum loading increase of 82% percentage points to the cables total loading capacity.

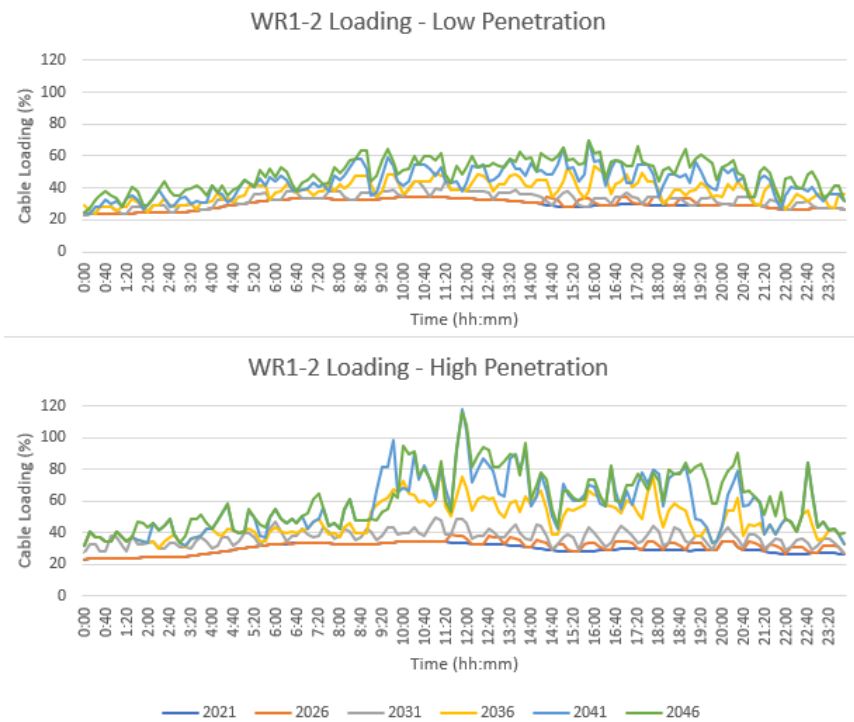

Figure 3: WR1-2 cable loading during low and high EV penetration scenarios over a 24 hour period, 2021-2046. The CYME model included non-EV demand on WR1-2.

The third largest EVCL, BR2-1, is represented with Figure 4. Despite being the largest EVCL on the BR2 substation transformer, demand from this EVCL does not overload any cables due to a lower number of hosted EVs. The cable directly connecting the distribution system and EVCL reaches a maximum of 45% of the cable load capacity. The average loading, especially from 10:00 to 20:00, increases considerably from low to high EV penetrations. Despite this, the maximum loading increases by only an additional 5% percentage points.

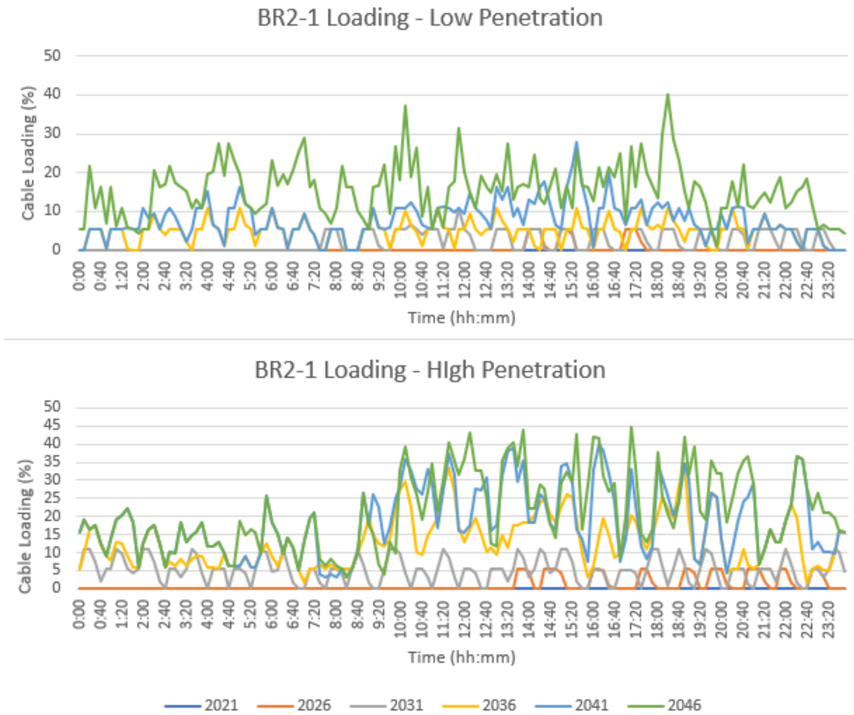

Figure 4: BR2-1 cable loading for low and high EV penetration scenarios over a 24 hour period, 2021-2046. The CYME model did not include any non-EV loading on BR1-1.

3.2.2 Other Cable Loading

Due to the large amount of EVCL loading on WR1-1 and WR1-2, several cables upstream from the EVCLs experience high loading, though loading levels only approach 100% under high penetration scenarios in later years.

Two cables were singled out in particular, as shown in Figure 5. These two cables share similar demand to WR1-1 and WR1-2, which are downstream. Both are within the Basin feeder, though not directly connected to any EVCL. The most significantly effected cable, PRUIG179129, experiences a nearly 80% percentage point increase between the 2021 and 2046 in high penetration scenarios. This increase is especially concerning as the surrounding cables do not show nearly as large a percentage point increase in loading. These cables should be noted as being susceptible to EVCL loading.

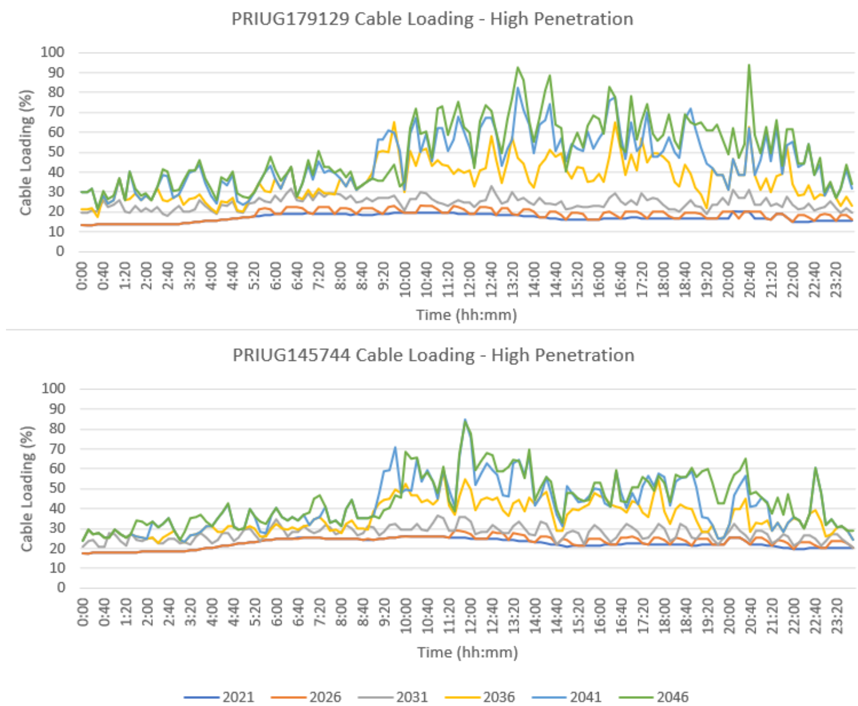

Figure 5: Non-EVCL cable loading under high penetration scenarios for two cables, PRIUG179129 and PRIUG145744.

3.3 Substation Loading

Two substation transformers serve the Swan Island distribution feeders. These transformers experience loading from each EVCL. Loading on transformer BR2, shown in Figure 6, does not experience much of an impact over the years of this study, just an additional five percentage points. This loading increase is mainly driven by BR2-1, the largest EVCL fed from BR2.

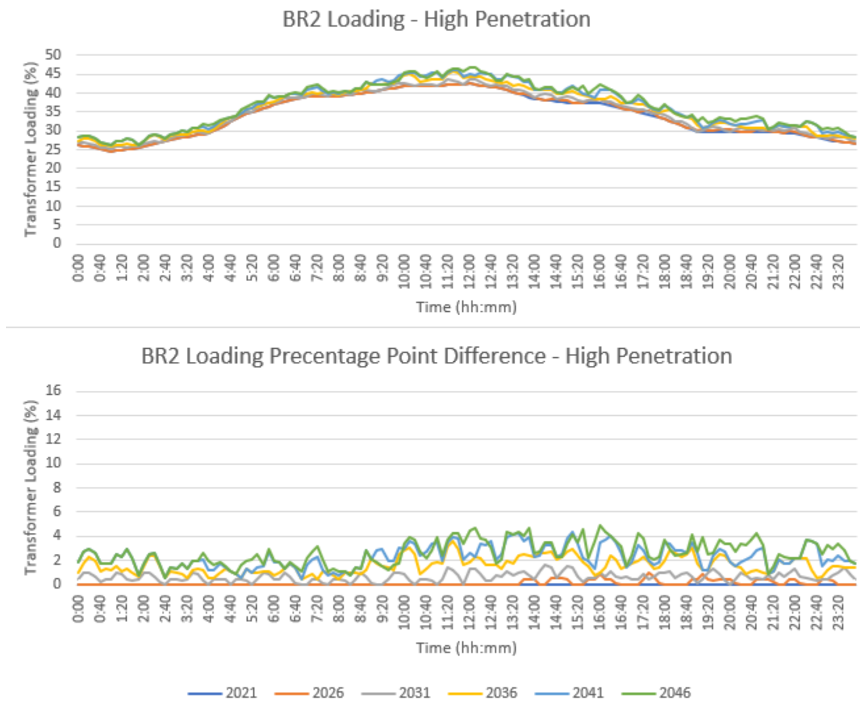

Figure 6: BR2 substation transformer loading (top) and loading difference with respect to the base case (bottom) due to EVCL for high EV penetration scenarios.

Substation transformer WR1 experiences large increases in loading, as it is the transformer that feeds the two largest EVCL installations, WR1-1 and WR1-2. Loading on this transformer is shown in Figure 7 for low penetration scenarios and Figure 8 for high penetration scenarios. This transformer has a maximum loading increase of 9 and 16 percentage points for low and high EV penetration scenarios, respectively. The largest total demand increase occurs during high EV penetration, peaking at 47%. The high penetration loading observed in Figure 8 causes a larger impact to average transformer loading when compared to maximum loading.

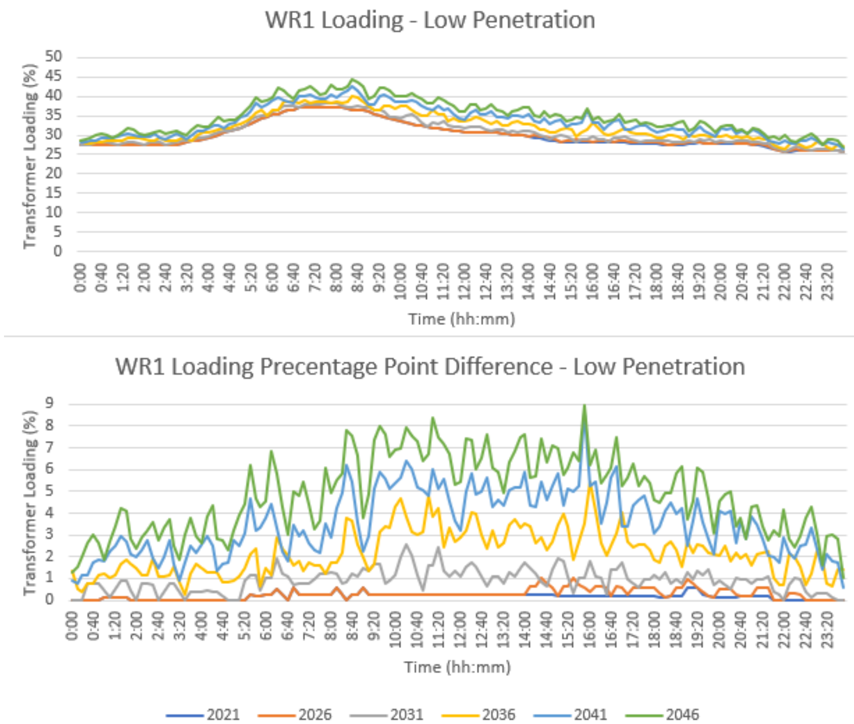

Figure 7: WR1 substation transformer loading (top) and loading difference with respect to the base case (bottom) due to EVCLs for low EV penetration scenarios.

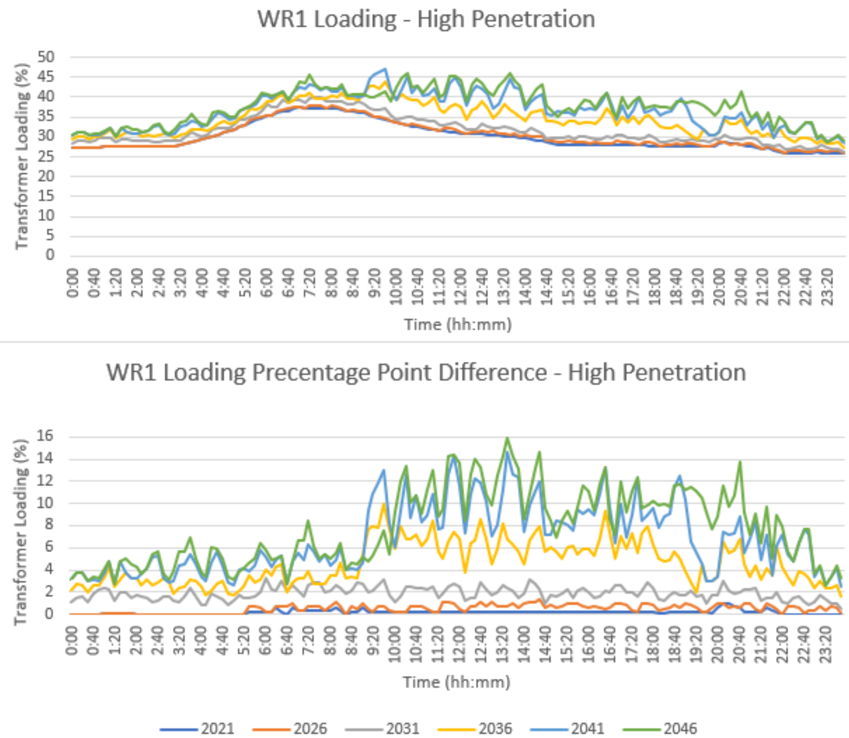

Figure 8: WR1 substation transformer loading (top) and loading difference with respect to the base case (bottom) due to EVCLs for high EV penetration scenarios.

3.4 Voltage Impacts

Voltage impacts due to EV charging events were studied using two metrics: distribution line voltage drop from the substation to the EVCL, and line-to-ground bus voltage on the utility side of the EVCL service transformer. Figure 9 shows where these voltages appear within a one-line diagram.

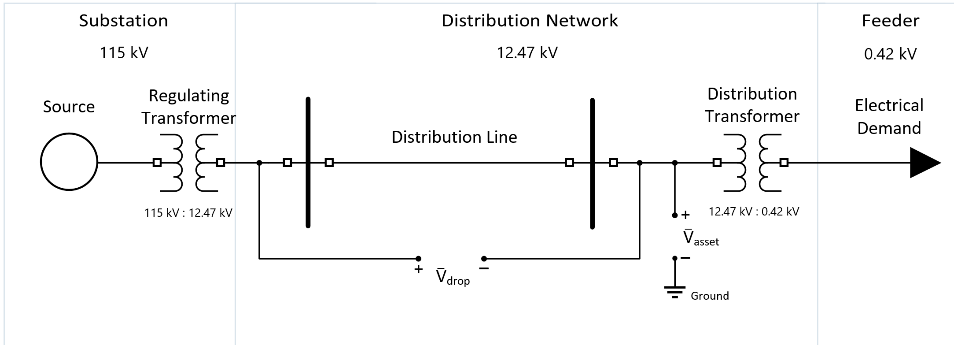

Figure 9: Graphic of voltage measurement locations for line voltage drop and line-to-ground asset voltage within a one-line diagram.

In Figure 9, line voltage drop is represented by V_{drop}. The line voltage drop metric is used to observe how EVCL demand impacts voltage drop across the conductors between the substation and the EVCL installations. Identifying this can allow EVCL demand impacts to be compared to the voltage drop impacting equipment attached to the EVCL.

EVCL line-to-ground bus voltage is labeled V_{asset} in Figure 9. Bus voltages are analyzed in order to understand how EV loading affects the EVCL high-side service voltages, and how these voltages are impacted by the regulating transformers at the substation (refer back to Figure 1). Bus voltage must be maintained within strict tolerances, ±5%.

3.4.1 Line Voltage Drop

The line voltage drop from substation to the EVCL transformer experiences only very small deviations with increasing EVCL demand. For the WR1-2 EVCL, these voltage deviations are shown in Figure 10. Voltage difference between the substation and the load is shown in the top plot. The change in voltage drop from the base case (with no EVCL demand) is shown in the bottom plot. The y-axis for these graphs are in per unit (pu), and are measured in thousandths. The largest increase in line voltage drop is just 0.0055 pu, which is just a 0.55% percentage point increase in voltage drop. This impact to voltage drop caused by EVCL demand is more clearly observed on the lower plot of Figure 10. Overall, despite the large increase to loading, as shown previously in Figure 3, the line voltage drop changed very little, which indicates there is no cause for concern for the voltage aspect of the EVCL installations. The Swan Island feeders are very stiff.

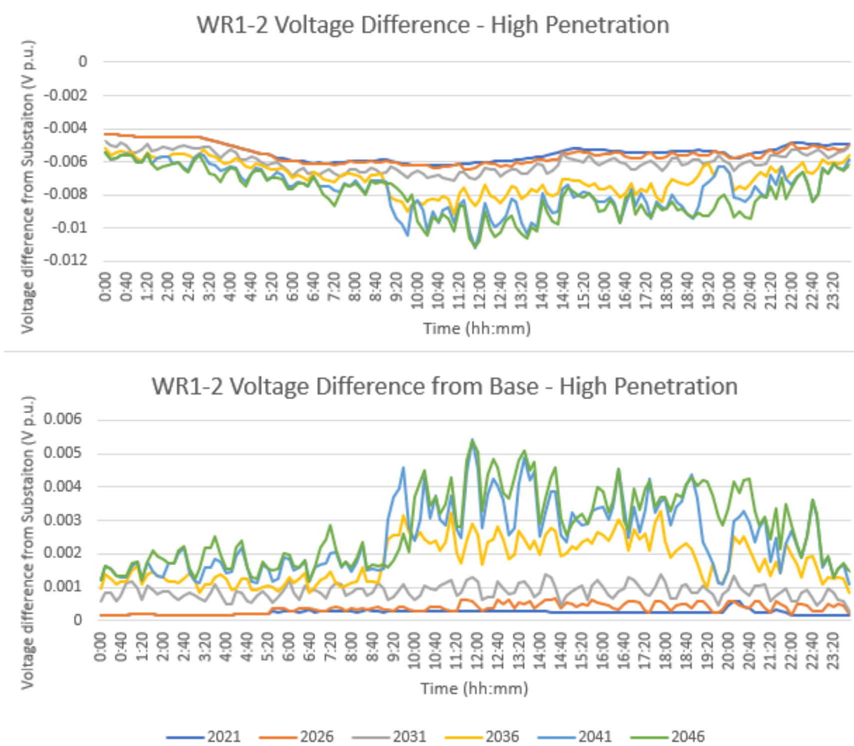

Figure 10: Voltage drop between the substation transformer and the WR1-2 EVCL under high penetration scenarios, absolute (top) and difference with respect to the base case (bottom).

3.4.2 Line-to-Ground Bus Voltage.

Line-to-ground bus voltage data are shown in Figure 11, which shows high-side transformer bus voltage for the high EV penetration scenarios. Sudden increases or decreases to input voltage in roughly 0.08 pu steps are due to tap changes by the regulating transformer at the substation. Note the bus voltage is maintained within a very narrow and acceptable range. For the 2046 forecast with the largest EVCL demand, the maximum deviation from the base case is just 0.006 pu, or a 0.6%. This figure clearly shows the substation transformers maintain load voltages even when EVCL demand is projected to be very high.

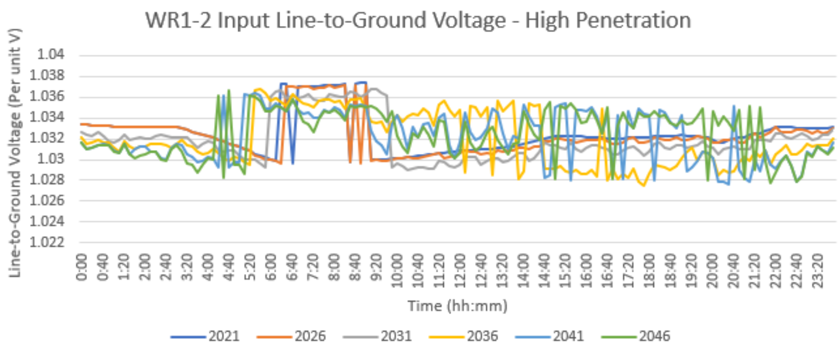

Figure 11: WR1-2 node line-to-ground bus voltage under high penetration scenarios. Voltage regulation action of the WR1 substation transformer is the cause of step voltage changes.

4 Time-of-Use Rates: Simulations and Analysis

The objective of offering Time-of-Use (ToU) rates is to incentives price-sensitive loads to shift consumption to periods of lower electricity costs. EV electricity consumption (charging) is decoupled from EV energy use (driving), so EV loads should be elastic with ToU pricing structures. The Swan Island CYME model provides an opportunity to study the potential affects ToU pricing could have on feeder asset loading when serving medium-duty EVs. PGE created ToU rates for both the summer and winter, as shown in Figure 12. Summer ToU rates are considered in this report.

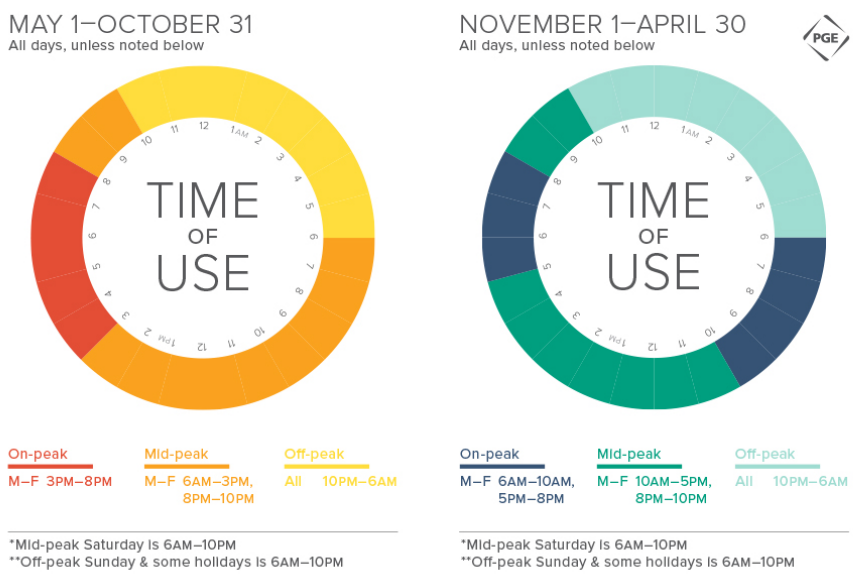

Figure 12: PGE Time-of-Use rates, weekdays in summer (left) and winter (right).

4.1 Time-of-Use Scenarios

Two sets of loading scenarios were created for this study. In one, EV loads shift from mid- and on-peak pricing hours towards off-peak pricing hours. In the second, EV loads shift towards mid-peak pricing hours. High penetration scenarios where considered for the study years between 2021 and 2046. These two loading scenarios where created by shifting the center of the base-case demand profiles. The off-peak demand profiles were shifted to center around 2:00 AM. The center of the mid-peak profiles were shifted to 10:30 AM. The base-case loading scenarios center around 12:00 PM to 1:00 PM. These scenarios consider loading of the EVCL WR1-2 because of the heavy EV loading demonstrated in 3.2.1 and because WR1-2 is the one EVCL that also includes non-EV loading.

4.1.1 Scenario 1: Shifting Towards Off-Peak Hours

Figure 13 shows two scenarios of loading experienced by EVCL WR1-2 under the high-penetration scenarios between 2021 and 2046. Without time-varying prices, EVCL loading patterns show peak demand during the late afternoon and early evening, as shown in the top plot of Figure 13. This overlaps with PGE's summer mid-peak and on-peak ToU periods. The middle plot of Figure 13 shows shifted profiles, which results when EV charging demand shifts to periods of lower ToU pricing.

The bottom plot of Figure 13 shows the difference in average loading for each hour time segment between the top and middle plots, with color coding that corresponds to the summer ToU periods shown in Figure 12. The top two plots show the high penetration scenarios in years 2021 through 2046. The bottom plot shows the average loading difference of 2046 demand profile for the low, medium, and high EV penetration scenarios. This plot shows that load shifts from afternoon and early evening periods to late evening and morning periods at each of these three penetration scenarios.

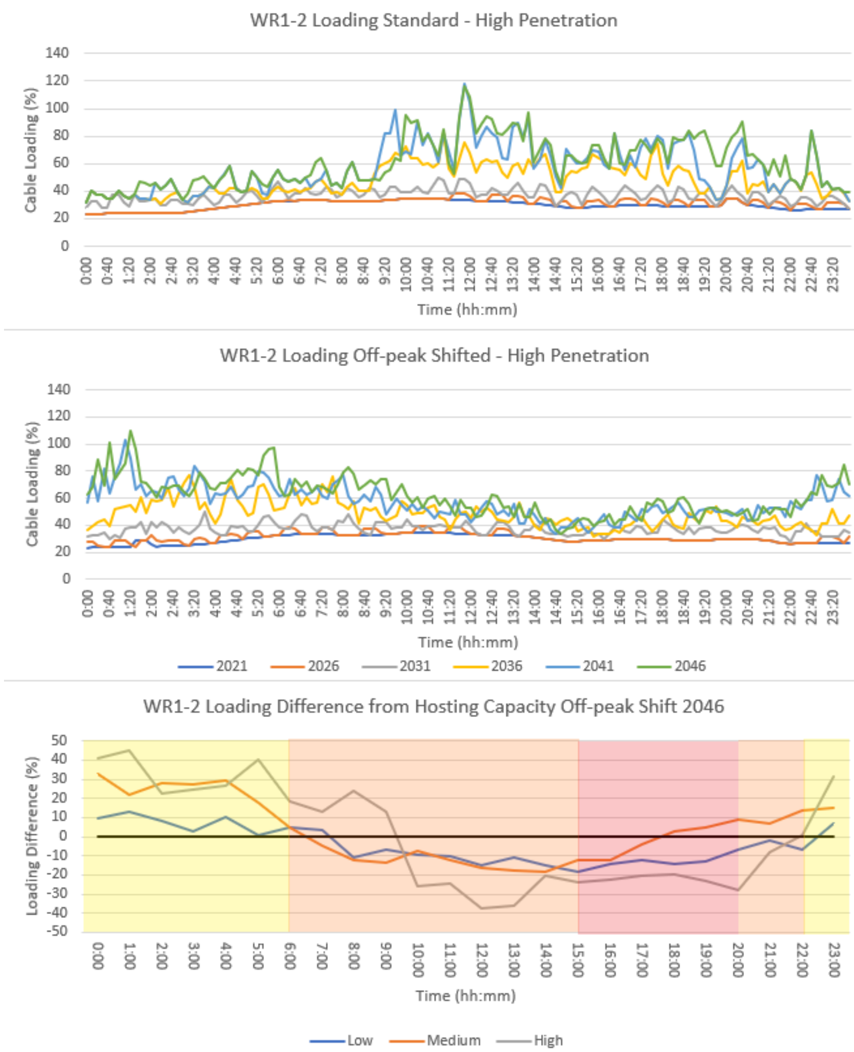

Figure 13: Impact to WR1-2 loading due to off-peak demand shifting. Color coding in the bottom plot corresponds to summer ToU periods in Figure 12.

4.1.2 Scenario 2: Shifting Towards Mid-Peak Hours

Figure 14 shows loading profiles for the second scenario. This scenario assumes EV owners are sufficiently incentivised to shift charging from on-peak to mid-peak periods, resulting in similar, but less dramatic load-shifting. Overall, these two ToU demand profiles demonstrate lower peak loading during on-peak hours in comparison to the non-ToU hosting capacity scenarios. The impacts on transformer and cable assets are discussed below.

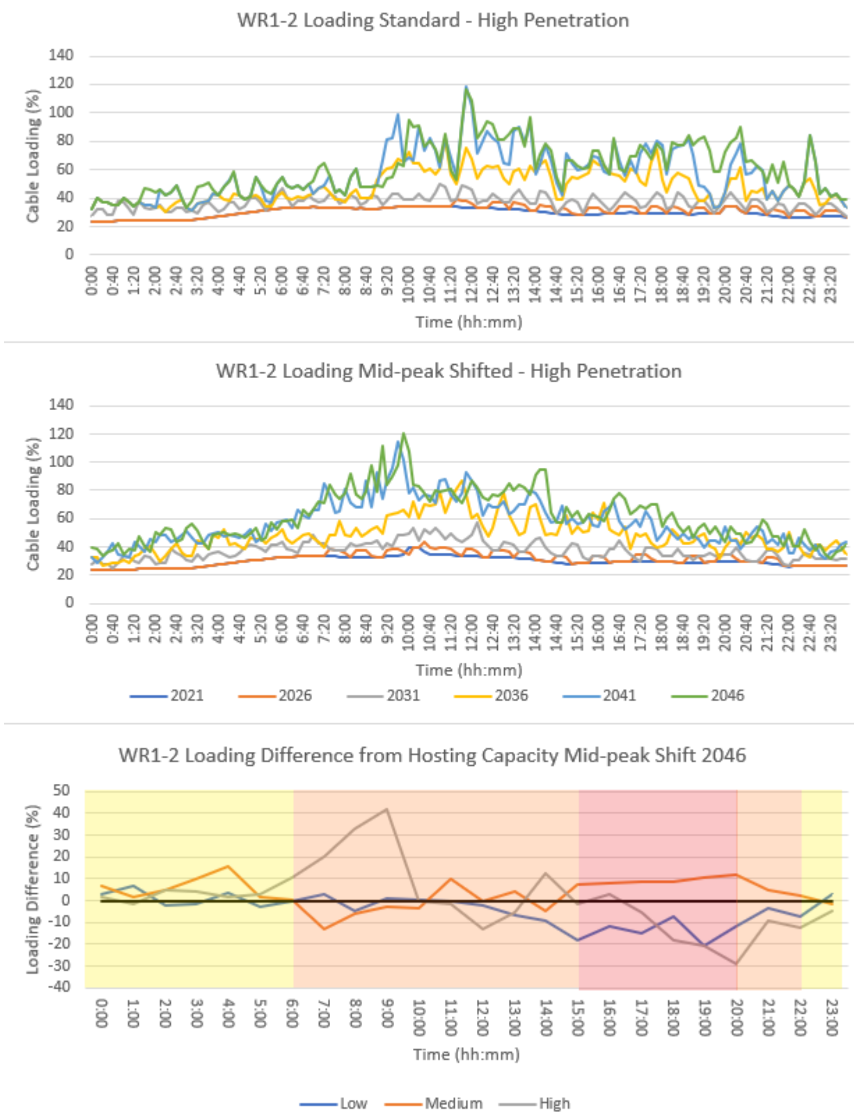

Figure 14: Impact to WR1-2 loading due to mid-peak demand shifting. Color coding in the bottom plot corresponds to summer ToU periods in Figure 12.

4.2 Analysis

By design, ToU pricing structures should result in reduction of on-peak loading. The purpose of this ToU study is to examine how EV charging that has been incentivized to shift charging times by ToU pricing would alter impacts on utility assets. This study assumes EV charging does behave in this way; it does not consider the behavioural relationships between pricing and operator charging habits.

To understand loading impacts of time-shifted EVCLs, the cable feeding EVCL WR1-2 is monitored. Loading differences for this EVCL seen in the bottom plot for Figure 13 and Figure 14 can be found numerically represented in Appendix B. Loading within this cable is equal to the loading that would be experienced by the distribution transformer that feeds this EVCL. By examining this cable, we can understand the peak loading and periods of high-load that would inform sizing of this EVCL transformer; and whether the power rating of the transformer can be lower if ToU pricing effectively shift demand. Peak loading can be found below in Table 2. This table includes the maximum loading value observed for WR1-2 at each low, medium, and high EV penetrations, for the base hosting capacity case, as well as for off and mid-peak shifted ToU EV charging. The difference between hosting capacity base case maximum loading and ToU shifted maximum loading can be found directly to the right of each ToU shifted column.

Analyses consider the following:

- changes in the magnitude of peak loading within the WR1-2 cable
- duration of high-load periods

WR1-2 Maximum Loading Percentage and Impact due to EV ToU charging - Year 2046					
EV Forecast	Base Case	Off-Peak	Loading Difference	Mid-Peak	Loading Difference
Low	70	56	-13	62	-8
Medium	90	81	-9	86	-4
High	117	110	-7	121	+4

Table 2: Maximum loading percentage and impact from ToU demand shifting for 2046 high penetration.

4.2.1 Shifting to Off-Peak Hours

Impacts that occur due to off-peak EV charging are shown in Figure 13. The peak EVCL loading plotted in the top two graphs clearly show a shift into the off-peak period. For high penetration scenarios, there is a roughly 20% percentage point decrease loading from 15:00 to 20:00, and a 30% percentage point increase in off-peak loading from 22:00 to 6:00.

A 20% percentage point decrease in on-peak loading can ensure fewer breaker trip events. The 30% increase in off-peak loading, however, will not cause much of an impact on the surrounding equipment as this is the lowest period of demand. Impact to maximum asset loading are shown in Table 2. Off-peak shifted ToU charging for the high penetration forecast shows a 7% percentage point maximum loading decrease. This maximum loading decrease includes both the impact of ToU shifted demand profiles as well as Swan Islands load shape mentioned in Section 3. In this case, the mid-peak loading does not change much overall due to both a loading increase from 6:00 to 9:30, and a loading decrease from 9:30 to 15:00. Overall this off-peak EV charging causes a favourable impact to the grid during the on-peak period, while increasing the EV charging during early hours.

4.2.2 Shifting to Mid-Peak Hours

Mid-peak shifted EVCL demand profile impacts are shown in Figure 14. This figure shows less of an increase for off-peak loading, and a larger mid-peak impact. The mid-peak period observes a large increase to loading until 10:00. On-peak demand causes an average of a 12% percentage point decrease to loading. The 12% percentage point decrease in on-peak loading can prevent transformer and cable overloading. This ToU-shifted EV charging does not have as large an impact as off-peak shifted charging, but is still beneficial to the system hosting capacity.

Maximum loading for the mid-peak shifted EVCL charging increases for the 2046 high penetration forecast. This increase is partially due to the load shape provided by PGE. The load shape has a maximum non-EVSE loading peaking during the mid-peak period of ToU rates. It is more likely that peak non-EVSE demand would occur during the on-peak ToU period rather than mid-peak or off-peak periods. This could lead to a larger decrease in maximum loading, caused from the system loading peaking during the on-peak ToU period from 15:00 to 20:00.

5 BESS: Simulations and Analysis

These BESS studies consider the impacts of BESS co-located with EV charging infrastructure. Two types of studies are considered. The studies examine how BESS charge/discharge profiles may be arranged to reduce impacts on utility assets. Analyses focus on loading within cables connected to EV charging infrastructure, which serve as a proxy for loading experienced by distribution service transformers.

Two studies are considered:

1. Co-location of BESS with EVCL
2. Coordinating BESS with in-route charging of municipal buses

5.1 Battery Energy Storage System Profiles

BESS profiles were created by specifying four criteria. These criteria include power capacities, energy capacities, charge/discharge start times, and charge/discharge durations. Power capacity indicates the maximum power the battery can charge or discharge, specified in kW. Energy capacity, expressed in *hours* or *minutes*, is the maximum charge/discharge duration that a battery can sustain while providing rated power. For these profiles, BESS were set to charge/discharge at constant rated power. Charge and discharge durations were determined based on how long elevated demand is anticipated to persist, and cannot exceed the energy capacity duration. Charge and discharge start times were set to align with periods of low and high loading, respectively. These four variables define the BESS profiles used in these studies.

5.2 Analysis

Analyses of BESS impacts on EVCL loads examine the following:

- Minimum BESS power and energy capacities required to reduce EVCL loading
- Impact on EVCL cable loading with and without co-located BESS
- Cost savings from shifting demand based on PGE ToU rates

5.2.1 BESS Schedule Coordination with TOU Pricing

BESS can be used to mitigate the impacts of EVCL loading on utility assets by shifting the load to periods of low demand. This impact is analyzed by considering two metrics: *mitigating peak demand* by shifting electrical demand to another time, and *reducing electricity cost* through PGE's ToU rates. Mitigation of peak demand reduces loading within both transformers and conductors, which may prevent overloading events from occurring. The reduction of electricity costs is an additional benefit when using BESS to mitigate peak demand. Demand offset during the peaking period can be shifted to off-peak hours, the lowest cost period of the day.

Mitigating Peak Demand

Loading for EVCL WR1-2 during high penetration scenarios is shown in Figure 15. The top plot shows WR1-2 loading without BESS co-location. The middle plot shows EVCL loading when supplemented with a co-located BESS. The bottom plot shows the percent loading difference between the two scenarios.

This EVCL WR1-2 is the largest EVCL on the Swan Island study with existing non-EVSE demand. For the high penetration studies observed in Figure 15, BESS reduce maximum EVCL loading by 20% percentage points in the 2046 scenario. This decrease occurs during the mid-peak period of ToU pricing, with a 630 kW, 4 hour discharge period BESS. Demand is shifted by charging the battery during an off-peak pricing period. Maximum demand reduction for the low penetration forecast in 2046 was observed as 5%, with a 8% decrease for 2046 during the medium penetration forecast. These low and medium penetrations use BESS with rated powers of 225 kW and 270 kW, and rated capacities of 4 hours.

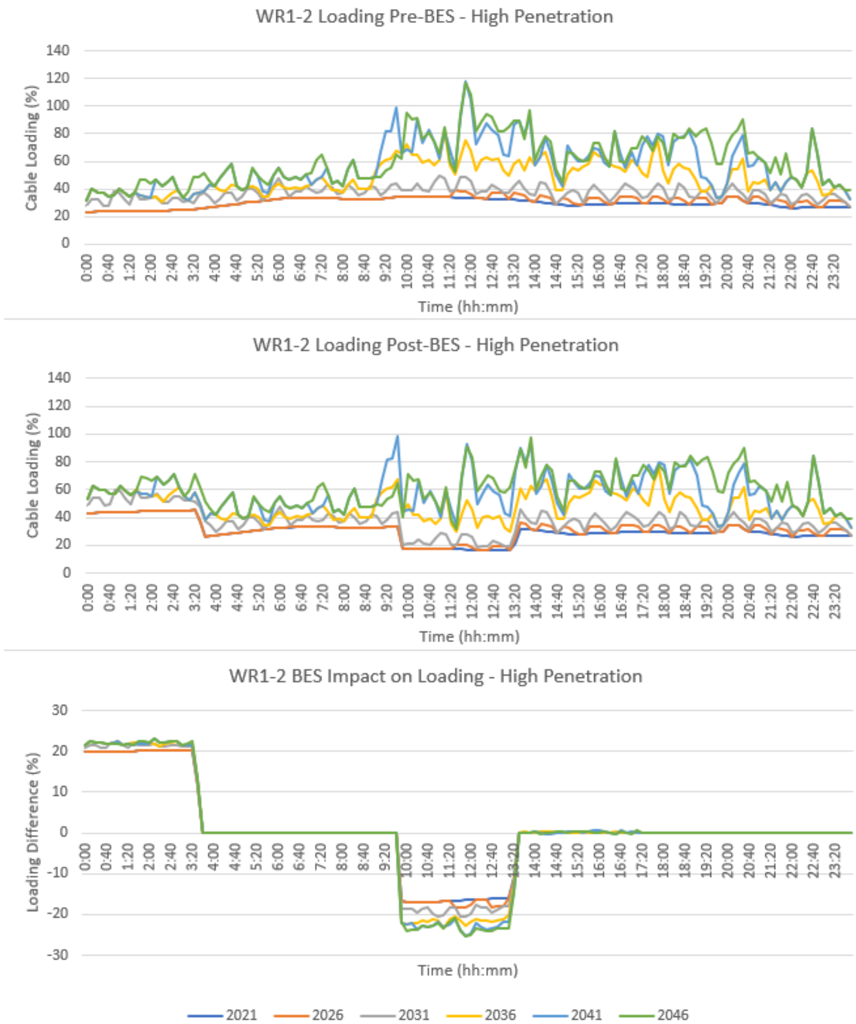

Figure 15: BESS impact on WR1-2 loading for high penetration scenarios. The top plot shows the hosting base case loading for WR1-2. The middle plot shows the loading on WR1-2 with the BESS included. The BESS loading impact is shown in the bottom plot.

Rreducing Electricity Cost

While peak demand mitigation is the focus of these analyses, cost savings are another potential benefit. Even with BESS focused on reducing peak demand, the deferment of loading from mid- or high-peak ToU periods to off-peak ToU periods can save customers money. This analysis is a rudimentary cost assessment, considering only customer energy costs savings that may accrue if demand is shifted from a mid-or high-cost period to a low-cost period. Neither time value of money nor capital, O&M, and other expenses are considered.

One year of cost savings was calculated by multiplying the cost savings for a day by 365 days/year. Cost savings and ToU shifts in demand for 2046 are summarized in Table 3. This table includes the cost savings per year and ToU shifts for each EV low, medium and high scenarios. For EVCL WR1-2, the high penetration scenario has a potential cost savings of $21,891 per year. This cost savings occurs when shifting from mid-peak ToU demand to an off-peak ToU period, as shown in the *high penetration* column for WR1-2 in Table 3. The low penetration forecast for WR1-2 has a larger cost savings than observed in the high penetration forecast. This is due to the low penetration forecast shifting demand from on-peak to off-peak ToU rates, while the high penetration shifts demand from mid-peak to off-peak. While shifting demand from on-peak results in the largest cost savings, shifting from mid-peak periods can also result in siginificant costs savings for customers.

Cost savings per year and how demand shifts over ToU rates for WR1-1 and WR1-2 - 2046						
EVCL	**Low**	**Demand Shift**	**Medium**	**Demand Shift**	**High**	**Demand Shift**
WR1-1	$9,381	Mid-Off	$18,763	Mid-Off	$48,859	Mid/On-Off
WR1-2	$22,719	On-Off	$9,381	Mid-Off	$21,891	Mid-Off

Table 3: Cost savings and demand shifts for WR1-1 and WR1-2 for EV forecasts, 2046 scenario.

5.2.2 BESS Placement within Municipal Bus Routes

An EVSE serving municipal buses within an established route presents volatile demand, ranging from several hundred kWs at one moment to near zero the next. A single bus will spend around ten to twenty minutes charging at an in-route EVSE prior to cycling through a route for around two hours, as shown in the SOC profile of Figure 16.

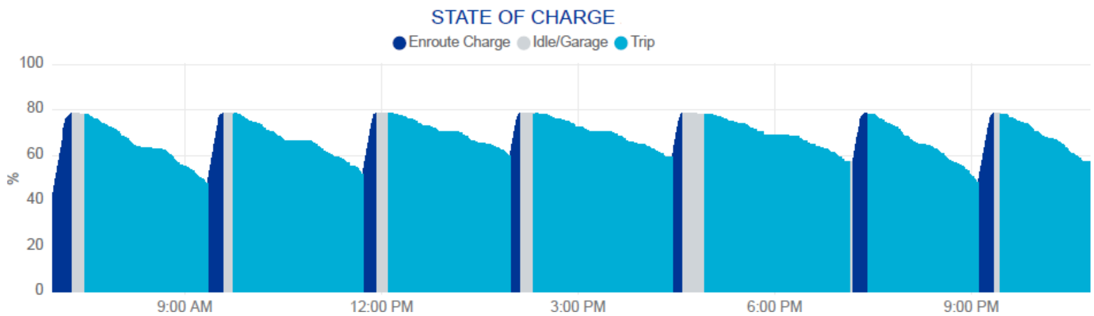

Figure 16: A single bus will spend a brief period charging at an in-route EVSE prior to driving through its route for several hours.

A single bus route may be simultaneously served by three to five buses, resulting in volatile demand on the in-route EVSE as buses periodically pull in to recharge, as shown in the top plot of Figure 17. This particular profile shows EVSE demand due to multiple buses periodically charging as they cycle through the same route. Power volatility results as buses pause their route to briefly charge. The EVSE is then unused for a period before the next bus arrives to charge. The peak power of a highly-utilized EVSE can be much larger then the average power because of the on/off nature of this charging profile.

A BESS co-located with in-route EVSE can reduce peak power and remove load volatility at the Point of Common Coupling (PCC). EVSE demand can be effectively offset using relatively small BESS. For single EVSE, when EVs are not actively charging, the demand is zero. These periods of zero demand can be used to effectively charge BESS between EV charging events.

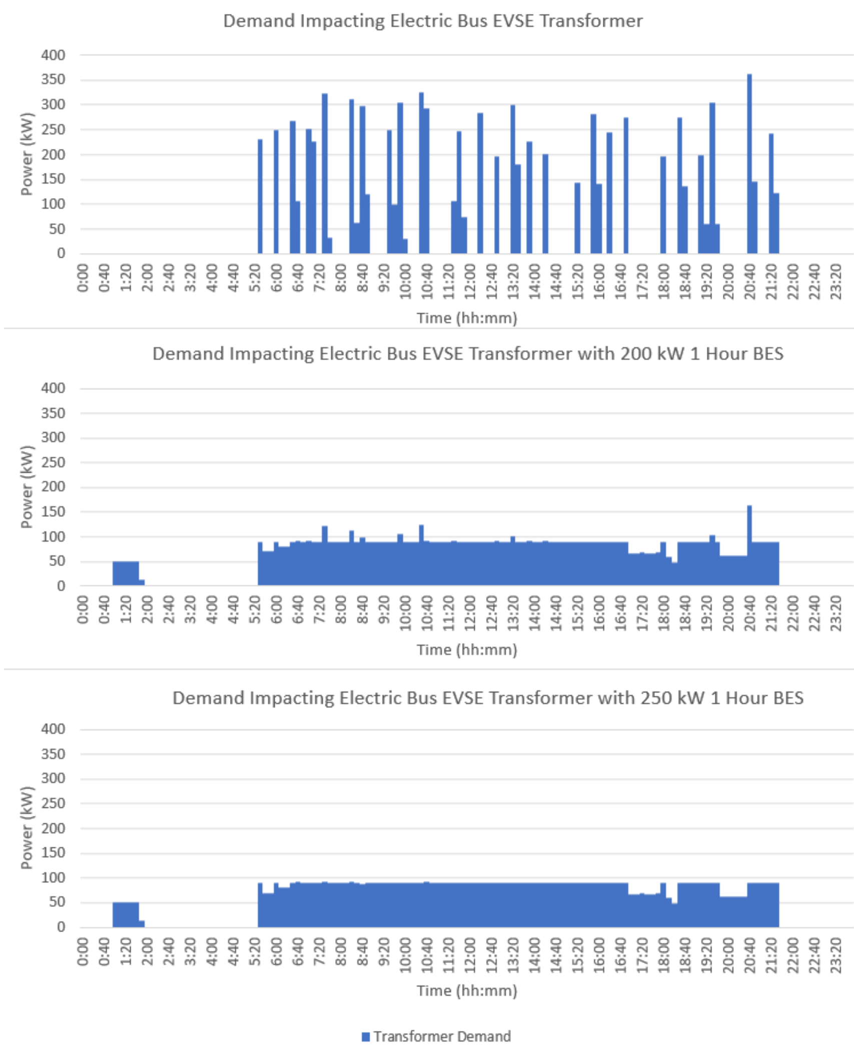

Figure 17: BESS impact on the transformer feeding an electric bus EVSE. The top most graph shows electric bus demand on the transformer without a BESS. The middle and last graph show the transformers demand with a 200 kW BESS and a 250 kW BESS respectively.

Juxtaposed with the base EVSE demand profile, Figure 17 also shows the impact a BESS can have on the net demand at the PCC, in the middle and bottom plots. The middle and bottom plots show total demand at the PCC from both the BESS and EVSE for a 200 kW battery and a 250 kW battery, respectively. Both BESS have a 1 hour energy capacity. While the 200 kW BESS decreased the majority of demand, one spiking period reaches 160 kW. This is significant compared to the average of 90 kW. This brief, larger period of loading could be a concern for cable overloading, but due to the small time period, it would likely not cause transformer overloading. Using a 250 kW, 1 hour BESS, the load profile reduces from a maximum of 360 kW to just 110 kW, with the vast majority of the profile at around 90 kW.

These scenarios show that BESS can effectively offset peak periods of demand. The on/off cycle of loading observed in the top plot of Figure 17 allows a BESS to manage charge and discharge in order to achieve a certain level of near-constant demand. BESS discharging occurs whenever a bus is charging. Charging occurs whenever the EVSE is disconnected during bus service hours.

Using a BESS in this manner provides a non-wires solution to the challenges of expanding municipal electric bus service. Periodic and frequent high power consumption from in-route EVSE may present stress to utility assets at locations where bus charging is needed but the electric infrastructure is not up to task. A co-located BESS can enable the installation of a high-capacity EVSE at feeder locations without need for expensive wired solutions to increase capacity.

A co-located BESS provides solutions to two problems:

1. The need to restring cables between the PCC and the upstream feeder service.

2. The necessity of purchasing a transfomrer with a rated power equal to that of the EVSE.

The cable loading reduction is fairly straightforward. The BESS charges while the EVSE is idle and discharges while the EVSE is servicing a bus. As such, the feeder and the BESS share the load while the bus charges, thereby reducing load impacts on the cable.

Likewise, the service transformer power rating can be significantly less than the rated power of the EVSE if the BESS energy capacity is properly considered. Depending on the size of the BESS, transformer rating could decrease by more than half depending on the frequency of of EVSE use at the in-route charging location.

6 Conclusion

PSU studied PGE's Swan Island study in order to identify distribution system impacts from EVCLs serving medium-duty vehicles. The Swan Island substation serves a large industrial customer base, which PGE expects will adopt medium-duty EVs in large numbers over the coming years. PSU conducted analysis of hosting capacities, ToU load shifting, and BESS placement within the Swan Island study in order to understand how wide-scale adoption of medium-duty EVs could impact distribution system assets and how BESS could be used to provide non-wire solutions to these impacts. By identifying potential problems and possible solutions, PGE distribution planners can proactively take steps to prepare for large-scale medium-duty EV adoption, not only within the Swan Island service area, but throughout PGE's service territory.

PSU created load profiles of several medium-duty Electric Vehicle Charging Locations within the Swan Island service area, with forecasts spanning 2021 to 2046 in five-year increments. Each forecast year includes three projected penetration levels: low, medium, and high. EVCL demand profiles consist of a superposition of multiple EV charging events, using medium-duty EV battery power capacities ranging from 80 kW to 200 kW.

EV loading levels become very large in the later years of these studies. It is only in these later years under high-penetration scenarios that we observe overloading of assets. For instance, in the 2046 high EV penetration scenario, two cable assets within the system become overloaded. These are the cables connecting the EVCL to the distribution service transformer. One of these cables is overloaded from just EVSE demand, WR1-1, while the other, WR1-2 becomes overloaded due to a combination of existing and EVSE demand, though largely the latter. The substation transformer for the Basin feeder, WR1, experiences at most a 16% percentage point increase to loading, or an additional 10% percentage points to maximum loading when feeding EVCLs. Two cables which are not directly connected to the EVCL are impacted by EVCL loading considerably more so than near-by cables. Changes to system voltages are minimal compared to impacts on cables and transformers. Line voltage drops are small and increase only slightly with loading. High-side transformer line-to-ground voltages at the EVCLs show little difference from the base case, largely due to the actions of the voltage regulating transformers at the substation.

Shifting EV charging events by introducing ToU rates can lead to benefits. The WR1-2 EVCL experienced the largest benefit from ToU-induced load shifting. For high EV penetration scenarios in later years, ToU shifted demand causes a reduction in overall maximum loading by up to 7% percentage points. Off-peak shifted demand results in a 20% percentage point decrease from on-peak loading, preventing possible overloads. While off-peak loading increased by 30% percentage points, there is little demand during off-peak periods, so potential overloading may be mitigated. Shifting load to mid-peak ToU periods reduces demand by an average of 12% percentage points compared to on-peak. Both off- and mid-peak ToU period demand shifting results in reductions in peak loading within the Swan Island study.

Co-location of BESS with EV charging infrastructure can ameliorate loading impacts of both medium-duty EVCL and in-route municipal bus EVSE. BESS co-located with EVCL may also result in cost savings for customers through demand deferment and ToU pricing.

Two BESS profiles focused on peak demand mitigation were studied: for EVCL WR1-1 and WR1-2. Again, the Swan Island system experiences loading problems mostly in the latter years of the study, and under high penetration scenarios. The high penetration 2046 forecast for EVCL WR1-2 shows on-peak load decreases by 20% percentage points, with a 30% increase to off-peak loading, when co-located with a BESS. This can prevent overloading events during the on-peak period for highly loaded assets. In additional to the loading reduction, this BESS results in a possible savings per year of $21,891. This sum is based off shifting demand from mid to off-peak ToU rates.

In-route municipal bus EVSE can benefit considerably from co-located BESS. By setting BESS to charge when the EVSE is disconnected, a relatively small BESS can reduce the service cable and transformer rating requirements. For example, studies showed a co-located BESS reduces peak loading from 360 kW to 110 kW. This reduction in peak demand would permit municipal bus EVSE to be placed within distribution feeders that would otherwise not have the capacity to host such large loads.

PGE provided EV forecasts for the Swan Island distribution system that project significant growth in EVCL loading over the coming years. Overall, PSU's analysis found the Swan Island system to be robust in terms of voltage, and it experiences few asset overloads in all but a few scenarios. The system experienced overloading only during the latter study years, and only under high penetration forecast scenarios. WR1-1 and WR1-2 both experienced overloading due to EV charging. However, the overloading on WR1-1 was due solely to EVCL; a base load was not included within this EVCL load profile. Both EVCLs have the potential to cause overload issues under high penetration scenarios in later years. ToU pricing may be effective in inducing operators to shift charging away from on-peak hours. Doing so was found to have a potential positive impact on distribution assets, with a larger impact observed when shifting to off-peak periods. BESSs co-located with charging infrastructure reduce overloading on those charging assets, and also reduce loading on up-stream assets. BESSs also have the potential to produce cost savings through peak demand mitigation.

These analyses found that Swan Island has well-controlled voltages and sufficient loading capacity to accommodate most EVCL load growth scenarios. Operators influenced by ToU pricing may help alleviate loading by shifting EV charging to mid- and off-peak hours. Co-located BESS can be used to support high levels of EV adoption, specifically medium-duty industrial vehicles and municipal buses, in the near-term without incurring the expense of major distribution system upgrades.

A Appendix: PSU Python-CYME Tools

The PSU Power Engineering Group created a suite of tools in order to conduct EV impact analysis. These tools use Python scripts to control and exchange data with CYMDist. The tools include: the *stochastic residential EV* tool, the *intentional EVSE* tool, the *system growth* tool, the *time series* tool, and the *data collections* tool. These tools are publicly available within a persistent archive hosted by PSU's PDXSholar [1]. The MS Thesis by Sheeran describes the development of these tools, and provides examples of their use [2]. PSU has written a *CYME Python Help Guide* and a *CYME User Guide*, available upon request.

The *stochastic residential EV* tool provides means for stochastic placement of residential EVSE. The *intentional EVSE* tool takes user input for the creation of new EVSE on the system that are planned installations. For system growth not related to EVs, the *system growth* tool applies electrification factors to simulate the grid at a future date. The *time series* tool allows time series demand profiles to be applied and the impact to the grid to be observed at each time step. The *data collection* tool is used for gathering, sorting, and outputting interested qualities.

A.1 Stochastic Residential EV tool

The *stochastic residential EV* tool works mainly through two functions. The first function looks at the demand of each spotload in the CYME study. This demand value is used to estimate the number of EVs that will be placed on the study if 100% EV penetration was reached. The estimated number of vehicles at each household is used by the second function for this tool. This tool's other function places EVs stochastically across the system in order to reach the EV penetration. Each spotload on the system is given the same chance of having an EV applied, but only if there are still vehicles available as decided in the first function. EVs are only placed on spotload customers that are considered within CYME to be residential.

A.2 Intentional EVSE tool

The *intentional EVSE* tool creates non-stochastic EV load growth profiles. This tool takes input from the user to create EVCLs within the CYME study. These intentional locations each have a demand profile attached based on the order of entry, which will tell CYME what demand values to use at each point in time. This tool was created for flexibility, allowing users to decide the transformer rating as well as the number of EVSE and what sizes exist at the location. This was the tool used to install each EVCL in the Swan Island CYME study.

A.3 System growth tool

System growth not related to EVs is applied via CYME using the *system growth* tool. This tool calls CYME to apply a percentage based loading increase to all non-EV demand. This loading increases is per year, and uses the years taken from supplied EV penetration forecasts. For the Swan Island studies, the load growth percentage is set to zero.

A.4 Time Series Tool

The *time series* tool prepares time series profiles, such as demand profiles. The base CYMDist package does not include time series capabilities. This tool creates these capacities. In order to run time series simulations, each new EV forecast is looped through for the time step duration of the study. Inside of these time step loops, new demand values are applied to the whole system, which is then recorded by the data collection tool. This tool, working in tandem with the data collection tool, allows time series simulations to be run.

A.5 Data Collection Tool

The *data collection* tool gathers time series information, sorts it into a usable format, then outputs it into Excel documents. The first function of this tool is to gather the information between each time series demand. This information is collected into large arrays containing loading and voltage data for each time step and EV penetration. After the CYME simulations are complete, this tool gathers the data for each piece of equipment and creates Excel documents with each EV penetration. These EV penetrations are placed in different sheets into the Excel document for the type of equipment.

A.6 Using the Suite of Tools

Using this suite of tools involves a couple of pre-requisites. First, a valid CYME study must be provided in order to use this tools. Second, relationships linking demand of a household to the number of vehicles at the household must either created or supplied. Example data are publicly available the previously-mentioned PDXScholar archive. These tools must also be supplied with an EV penetration forecast, even if there are no residential households on the study. Profiles for Level I and Level II EVSE can be created internally, or examples can be retrieved from the PDXScholar archive. Once the documents mentioned above are gathered, simulation values must be chosen. These include initial EV penetration, final EV penetration, and step size between to use between the initial and final penetration. After this, the time steps for the study are chosen, with the initial time step and the duration of the study. Intentional EVCLs can either be input manually, or have the intended information stored in Python to run without user input. This includes the nearest spotload to the planned installation, the three phase power rating of the EVSE transformer, which phases it serves, secondary voltage, and demand profile for EVSE.

B WR1-2 ToU Loading Difference Tables

Percentage point change in loading due to ToU shift over 1 hour segments 0 - 11													
ToU Period Shift	Time Block	0	1	2	3	4	5	6	7	8	9	10	11
Off-Peak	Low	9	13	8	3	11	1	5	3	-11	-7	-9	-10
	Medium	33	22	28	27	29	17	5	-5	-13	-13	-7	-12
	High	41	45	23	24	27	40	18	13	24	13	-26	-24
Mid-Peak	Low	3	7	-2	-2	3	-3	0	3	-5	1	0	0
	Medium	7	1	5	10	16	1	0	-13	-6	-3	-3	10
	High	2	-1	5	4	2	3	10	20	33	42	0	-2

Table 4: Hourly average for WR1-2 loading difference using ToU shifted EV demand from 0:00 to 11:59. This impact is observed for Summer ToU rates. Yellow and orange columns represent off-peak and mid-peak ToU periods respectively. These colors were chosen to match with PGE summer ToU rates from Figure 12.

Percentage point change in loading due to ToU shift over 1 hour periods 12 - 23													
ToU Period Shift	Time Block	12	13	14	15	16	17	18	19	20	21	22	23
Off-Peak	Low	-15	-11	-15	-18	-14	-12	-15	-13	-7	-2	-7	7
	Medium	-17	-18	-18	-12	-13	-4	3	5	9	7	14	15
	High	-37	-36	-21	-24	-22	-20	-20	-23	-28	-8	1	31
Mid-Peak	Low	-2	-7	-9	-18	-12	-15	-7	-21	-12	-3	-7	3
	Medium	0	4	-4	7	8	8	8	11	12	5	2	-1
	High	-13	-5	13	-2	3	-5	-18	-21	-29	-9	-12	-5

Table 5: Hourly average for WR1-2 loading difference using ToU shifted EV demand from 12:00 to 23:59. This impact is observed for Summer ToU rates. Yellow, orange, and red columns represent off-peak, mid-peak, and on-peak ToU periods respectively. These colors were chosen to match with PGE summer ToU rates from Figure 12.

References

[1] J. Sheeran. *Data from: Modeling Tools for Analyzing Electrical Power Distribution Systems Impacted by Electric Vehicle Load Growth.* Portland State University, Electrical and Computer Engineering Datasets, June 2021.

[2] J. Sheeran. Modeling tools for analyzing electrical power distribution systems impacted by electric vehicle load growth. Master's thesis, Portland State University, Paper 5682, June 2021.

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