Evaluation of the Impact of Heat Pumps in Skidegate, Haida Gwaii

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Executive Summary

Heat pumps were installed in every home in Skidegate, Haida Gwaii as part of a Skidegate Band Council-led initiative from January 2015 to September 2016. Funding was provided by Indigenous and Northern Affairs Canada, and for eligible households, through BC Hydro's Home Renovation Rebate program. Out of approximately 360 Skidegate households, 325 rebates were given to 287 different accounts. Skidegate is connected to the south Haida Gwaii grid, a Non-Integrated Area (NIA). Hydroelectricity supplies 70% of the annual electricity to the grid with diesel supplying the remaining 30%. This initiative was selected as a case study to explore the impacts of widespread heat pump installations in NIAs, focusing on changes in electricity consumption and assessing the potential for power quality issues.

The change in electricity consumption before and after the heat pump installations was determined using a multiple linear regression model, with outdoor temperature and heat pump installation periods. On average, households receiving a rebate decreased their electricity consumption by 413 kWh per year, or 2.9% of their total annual consumption. This corresponds to a decrease in customer electricity costs of $50 per year (assuming $0.12 per kWh). The annual per customer cost-of-service decreases $124 per year (assuming $0.30 per kWh), or $35,600 annually for all 287 rebated customers. Based on anecdotal information, it is likely that the heat pumps partially displaced supplemental fuels like wood and fuel oil for a significant portion of households. Households that were primarily electrically heated before the heat pump installations would therefore realize higher than average electricity savings, and households that did fuel switch would see an increase in electricity consumption, yet realize additional cost savings from reduced wood or fuel oil use that could not be quantified with available data.

Heat pumps use electrical motors to circulate the heating fluid, which may cause power quality issues that are not seen with electric resistance baseboard heaters. Given the high penetration of heat pumps on the small grid, there was a concern that power quality issues may increase after the installations. However, analysis of power quality data at medium voltage shows no indication that power quality issues have increased since the heat pumps were installed. To assess potential power quality issues undetectable at the medium voltage level, low voltage power quality meters were installed at three locations in Skidegate. Results were not available at the time of this report and will be assessed by BC Hydro's power quality group.

A survey was prepared in conjunction with the Skidegate Band Council to obtain more information on changes in supplemental fuel use, behavioural changes in space heating and cooling, perceptions of the installation process and changes in home comfort, and to identify educational opportunities. Results are expected to be available in the fall.

Introduction

The Skidegate Band Council (SBC) led an initiative to install heat pumps in every home in Skidegate, Haida Gwaii from January 2015 to September 2016. The initiative's goal was to reduce the community's reliance on diesel-generated electricity, reduce household energy costs, improve heating quality and home comfort, and in some cases, remove the burden of getting firewood and coordinating fuel oil deliveries, particularly for Elders. Initial funding was provided by Indigenous and Northern Affairs Canada, and BC Hydro gave rebates to eligible installations as part of its Home Renovation Rebate program. Skidegate is part of the southern Haida Gwaii electric grid, a non-integrated area (NIA). The grid is 70% powered by hydropower from an Independent Power Producer (IPP) and 30% by diesel operated by BC Hydro.

This project will be used as a case study to evaluate the impact that heat pumps have had on Skidegate households and the southern Haida Gwaii electric grid. This is done in two respects within this report. First, changes in residential electricity consumption from before and after the heat pump installations are evaluated. Second, potential impacts to grid power quality are evaluated due to the high penetration of the heat pump motors. Results from this study will inform follow-up with Skidegate customers as well as the development of Demand Side Management (DSM) program offers for NIA customers.

Changes in Skidegate Residential Electricity Consumption

Heat pumps were installed to provide electric heat using less electricity, and therefore at a lower cost, than baseboard electric heaters. BC Hydro provided rebates for eligible heat pumps where evidence of existing electric heating was provided (among other criteria). This section attempts to determine the change in electricity consumption from the heat pump installation. This is done both to ensure that the heat pumps are being operated as intended, and to determine how much local households may have reduced or eliminated their use of supplemental heating methods such as wood or fuel oil.

Data and Methods

To assess the degree of electricity conservation from the heat pump installation, the relationship between household hourly electricity consumption and outdoor temperature was examined for time periods before and after the heat pump installations. Changes in the relationship between electricity consumption and temperature from before and after the heat pump installations are used to determine the effect of the heat pump installations on electricity consumption.

Anonymized hourly electricity consumption data was provided for November 2013 to June 2018 for the 287 accounts that received a rebate. Forty households were eliminated from the analysis due to an excess of missing values over the analysis time period. From this data, the average household hourly consumption was calculated. Hourly outdoor temperature data from nearby Sandspit, Haida Gwaii (11 km away) for the same time period was used as a proxy for Skidegate temperature (Environment and Climate Change Canada). Heating degree hours (HDH) were calculated, using 18 ^{o}C as the baseline, by subtracting the hourly temperature from 18, and eliminating all negative values. HDH were converted to heating degree days (HDD) for analysis and figures shown at lower time resolutions than hourly. Consumption data for the average household that received a rebate and monthly HDD are shown in Figure 1.

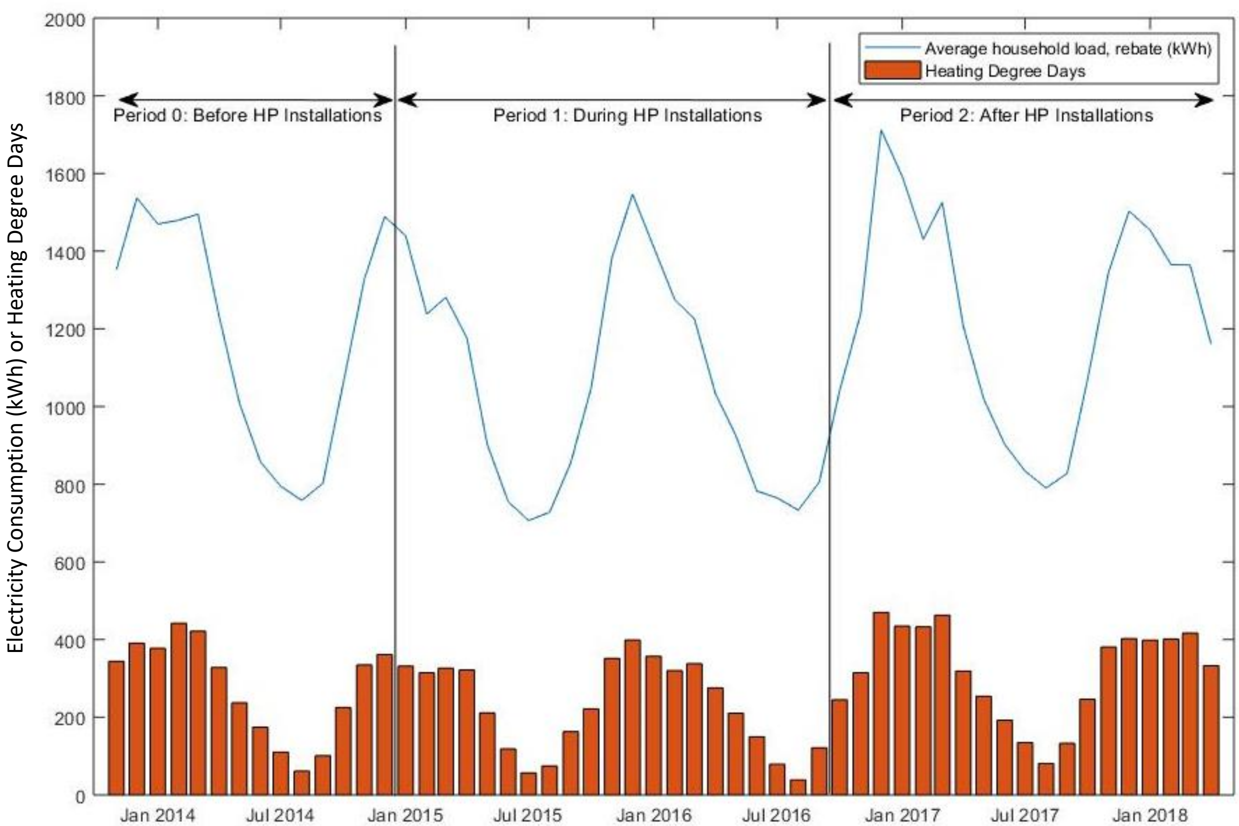

Figure 1: Electricity consumption data for the average rebate household and heating degree days. The heat pump installation periods are also shown, with installations occurring between January 2015 and September 2016.

The relationship between electricity consumption, HDH, and heat pump installation was assessed as part of a linear regression, represented by the following equation:

$$Consumption \cong \beta_0 + \beta_1 HDH + \beta_2 HDH{:}Install\_period$$

Heating degree hours are included with a linear and interaction term with the logistic installation period term to capture differences in the slope of electricity consumption compared to heating degree hours before and after heat pump installation.

Results and Analysis

Table 1 shows the variable regression coefficients and statistics. The intercept indicates that the average hourly household load not associated with heating is 0.845 kWh. The HDH coefficient indicates that for every 1^{o}C increase in HDH, the average hourly load increases by 0.0839 kWh. After the heat pump installations, the increase in average hourly load for every 1^{o}C increase in HDH decreases by 0.00513 kWh, to 0.0788 kWh. Based on the p-values, all variables have very high statistical significance.

Table 1: Regression coefficients

VARIABLE	COEFFICIENT	CI[1] – 2.5%	CI[1] – 97.5%	PVALUE[2]
(Intercept)	0.845	0.835	0.854	0
HDH	0.0839	0.0828	0.0850	0
InstallPeriod_1:HDH	-0.0057	-0.0068	-0.0047	6.74 E-27
InstallPeriod_2:HDH	-0.0051	-0.0061	-0.0042	3.44 E-27

[1] The 95% confidence interval, the values between which the coefficient is between with 95% statistical confidence.

[2] The p-value is the probability that no relationship between the variable and electricity consumption actually exists.

Table 2 provides a summary of regression model statistics. Based on the root mean square error, approximately 66% of the average household actual hourly data points will be within 0.393 kWh from the values predicted by the model. The R-squared value indicates that the input variables included explain approximately 45% of the overall variance in the average household consumption. Based on the F-statistic and p-value, the probability of the model explaining a spurious relationship is practically zero.

Table 2: Regression model statistics

DESCRIPTION	VALUE
Root mean square error	0.393
R-squared	0.45
Adjusted R-Squared	0.45
Model F-statistic vs. constant model	1.09e+04
p-value	0

Figure 2 shows the relationship between HDH and average consumption for rebated accounts. Electricity consumption is seen to decrease slightly at higher HDH after the heat pump installations. At an HDH of 18 ^{o}C (temperature of 0 ^{o}C), after heat pump installations the average household hourly electricity consumption decreases by 0.1 kWh, from 2.36 kWh to 2.26 kWh. The shift being slighter stronger in the period during the heat pump installations than the period after the heat pump installations does not match expected results. However, based on Table 1 the difference in relationship slope between these periods is not statistically significant, and could be spurious.

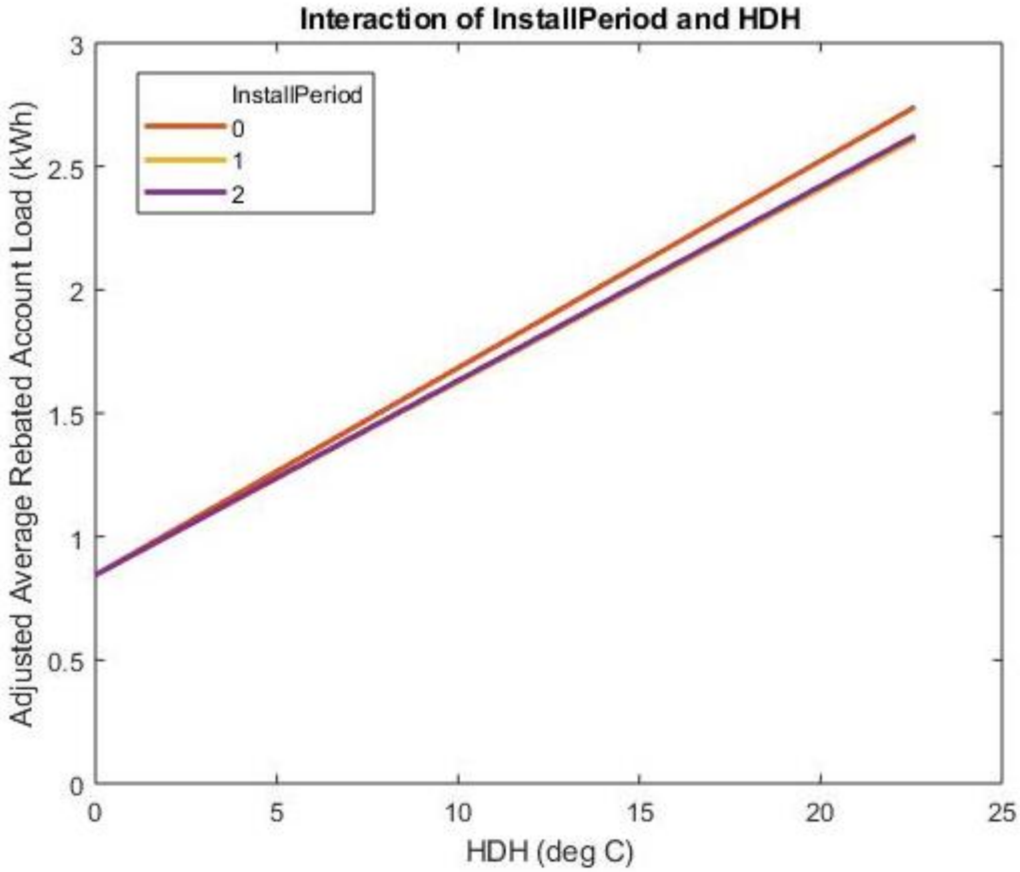

Figure 2: Average rebate household electricity consumption by heating degree hour, for before, during, and after heat pump installations. In periods during and after the heat pump installations, there is a shift downward in electricity consumption at higher HDH (lower ambient temperatures), indicating electricity conservation.

Regression results indicate a decrease in average household electricity consumption at higher HDH (i.e. lower temperatures). Based on the temperature data from July 2017 to June 2018, this led to a 413 kWh average decrease in annual electricity consumption, or a decrease of approximately 2.9%. At the NIA electricity customer cost of $0.12 per kWh, this will save the average customer $50 per year. Using the assumed NIA cost-of-service of $0.30 per kWh, the cost-of-service will decrease by $124 per year per customer. For all 287 customers who received a rebate, this is an annual cost-of-service decrease of approximately $35,600, assuming the 247 accounts on which the analysis was done are representative of the 40 customer accounts that were removed due to incomplete data requirements.

Analysis Limitations

The analysis determines the electricity savings for the average household. It is likely that subsets of households exist whose consumption differs significantly from the average value. In particular, many households in Skidegate are known to have supplemented electric heat with other fuel sources such as wood and fuel oil. Where the heat pump has significantly decreased or eliminated supplemental fuel use, households may have experienced a net increase in electricity consumption. Households that did not use significant amounts of supplemental fuels before the heat pump installations may have annual demand decreases much higher than 2.9%. More advanced statistical techniques could be applied at an individual household level to determine the effect of heat pump installations on individual households, but were not completed due to time constraints, and because of limited applicability due to the anonymous nature of the dataset. If installation dates matched to each account were provided, these techniques could improve the regression methodology by eliminating the use of the "during installation" categorical variable.

As the sole focus of this analysis is on electricity use, it does not capture the full effects of fuel switching. The additional potential cost savings or time savings associated with reduced supplemental fuel use could further increase the customer benefit but cannot be quantified from available data. Lastly, effects of the heat pump on home comfort have not been examined. A survey currently underway with the Skidegate Band Council is attempting to get a measure of some of these co-benefits and outcomes; unfortunately results are not yet available.

Methodologically, the analysis does not control for other potential changes in electricity consumption over time. Statistical methods attempting to accomplish this did not produce meaningful results, and a paired comparison to like households is not possible with the available data. The model is also restrained from considering some behavioural changes after the heat pump installations, such as differences in thermostat set points. This was done by restraining the intercept at an HDH of 0 from shifting up or down with the heat pump installation periods, and by considering a static HDH baseline temperature of 18 ^{o}C.

Power Quality Effects

Power quality issues are possible with 100% penetration of heat pumps in Skidegate particularly given the small size of the south Haida Gwaii electrical grid. Power quality metrics will be evaluated to determine if power quality has decreased since the heat pumps were installed.

There are multiple “paths” by which heat pumps may affect power quality. Possible sources of power quality issues from heat pumps include:

- Random coinciding motor inrush currents causing voltage sags, affecting medium voltage system and generator
- High motor inrush currents (possibly coinciding) causing voltage sags, localized to distribution system (likely downstream of last transformer)
- Power restart after an outage causes heat pumps to kick on at the same time, causing coinciding motor inrush currents preventing or delaying voltage recovery
- Exacerbating voltage dips

To note, the south Haida Gwaii electrical grid has three different configurations of generation: diesel only, hydroelectric (IPP) only and diesel/hydro cogeneration. Each configuration has different voltage regulation/excitation response. In particular, the hydroelectric IPP has a much slower voltage regulation response to load swings than if running only diesel.

Comparison of Starting Currents Between Appliances

An analysis of the installed heat pump models was conducted to determine the potential for inrush currents to affect the network. Key electrical parameters for the most commonly installed heat pump models in Skidegate are shown in Table 3, and compared to typical expected parameters for representative refrigerators. Data for the heat pumps are from manufacturer specification sheets, and data for the refrigerators are calculated from an analysis for the 2014 American Council for an Energy-Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings (Larson et al.).

Fujitsu ductless heat pump models make up 312 of the ~360 installations (87%). Fujitsu ductless heat pumps are installed with soft starters which significantly decrease the inrush current. The summarized Fujitsu models make up 73% of all the installed heat pumps. The starting currents and operating currents for these heat pumps are approximately equal to the expected calculated starting currents of representative refrigerators. Therefore, the potential for them to cause power quality issues is low.

Data is not available for an estimated 48 heat pump models for which BC Hydro did not provide rebates. Some of these 48 heat pumps are central heating models which are ineligible for rebates, and some may be Fujitsu ductless models where documentation required for the rebate was not able to be collected.

However, three central heat pump model numbers were identified from unsuccessful rebate applications. Assuming they do not have soft starters and their starting currents are equal to their locked rotor amps, the inrush current will be four to five times the expected calculated starting currents of representative refrigerators. The probability of these high starting currents causing power quality issues at a medium voltage level due to random coinciding starts is likely to be low due to their low installation rate of less than 13% of installations. The frequency of medium voltage power quality events over time is evaluated in the next section to confirm this. It is more likely that these inrush currents cause power quality issues at the low voltage level, particularly downstream of the last transformer.

Table 3: Equipment electrical parameter comparison.

Submittal sheet	Installations (of ~360) [a]	Heat Pump Type	Max operating compressor load (W)	Voltage	Max Starting Current (A)	Rated/ operating current (A)	Minimum Circuit Ampacity (A)	Max Fuse Size (A)	Power Factor	Locked Rotor Amps
Fujitsu 24RLXFZ	145	Ductless	2093	230	9.0	7.6-9.1	17	20		
Fujitsu 18RLXFW	60	Ductless	1840	230	14.5	6.2-8.0	N/A	20		
Fujitsu 15RLS3	33	Ductless	1196	230	5.2	4.8-5.2	17.2	20		
Fujitsu 36RLXFZ	27	Ductless	4623	230	15.1	14.1-20.1	20.1	30		
LENNOX XP17-024-230-09	<48 [b]	Central	3105	230		13.5	20	30	0.99	58.3
LENNOX XP17-030-230-10		Central	3243	230		14.1	20	30	0.99	63.0
LENNOX XP14-018-230-A10		Central	2070	230		9	12.2	20	0.98	48
Refrigerator, 20 ft^3 from 1995[c]	N/A	N/A	200	120	8.4 -16.7	1.67				
Refrigerator, 20 ft^3 from 2005[c]	N/A	N/A	125	120	5.2 -10.4	1.04				

[a] Fujitsu heat pumps make up at least 312 of the 360 installations, the most commonly installed models are summarized here.

[b] These 3 Lennox models were identified in unsuccessful rebate applications, but comprehensive data on the remaining heat pumps for which no rebates were provided is unavailable. They may all be central heat pumps which are ineligible for rebates, or some could be ductless Fujitsus where the documentation necessary for the rebate application was not provided.

[c] Refrigerator values from the 2014 ACEEE Summer Study on Energy Efficiency in Buildings. Maximum operating compressor load taken from typical operation, not the defrost load, which would be higher. Operating current is calculated from the power and voltage. Starting currents are based on the rule of thumb that inrush currents are 5 to 10 times the operating current.

Skidegate Medium Voltage Power Quality Indicators

Medium voltage power quality data from the south Haida Gwaii grid (from the SPT 25F52 ION meter) was assessed to determine whether power quality events have increased since the heat pumps were installed.

Power quality data was provided for January 1, 2014 to June 6, 2018 by the BC Hydro Power Quality team. This data, at 15-minute resolution, consists of the following variables:

- RMS phase-to-phase voltage (3)
- Voltage unbalance
- Current by phase (3)
- Power
- Reactive power
- Apparent power
- Power factor (PF)

The minimum, average, and maximum over the 15-minute period is provided for all variables except PF.

Three different power quality indicators were assessed:

- The count of 15-minute periods with a full outage
- The count of 15-minute periods with minimum voltages lower than thresholds of 90% and 95% per unit (p.u.)
- The count of 15-minute periods with minimum voltages lower than thresholds of 90% and 95% p.u. and maximum voltages higher than thresholds of 110% and 105% p.u., respectively

All per unit (p.u.) values were calculated using a 25 kV nominal distribution voltage.

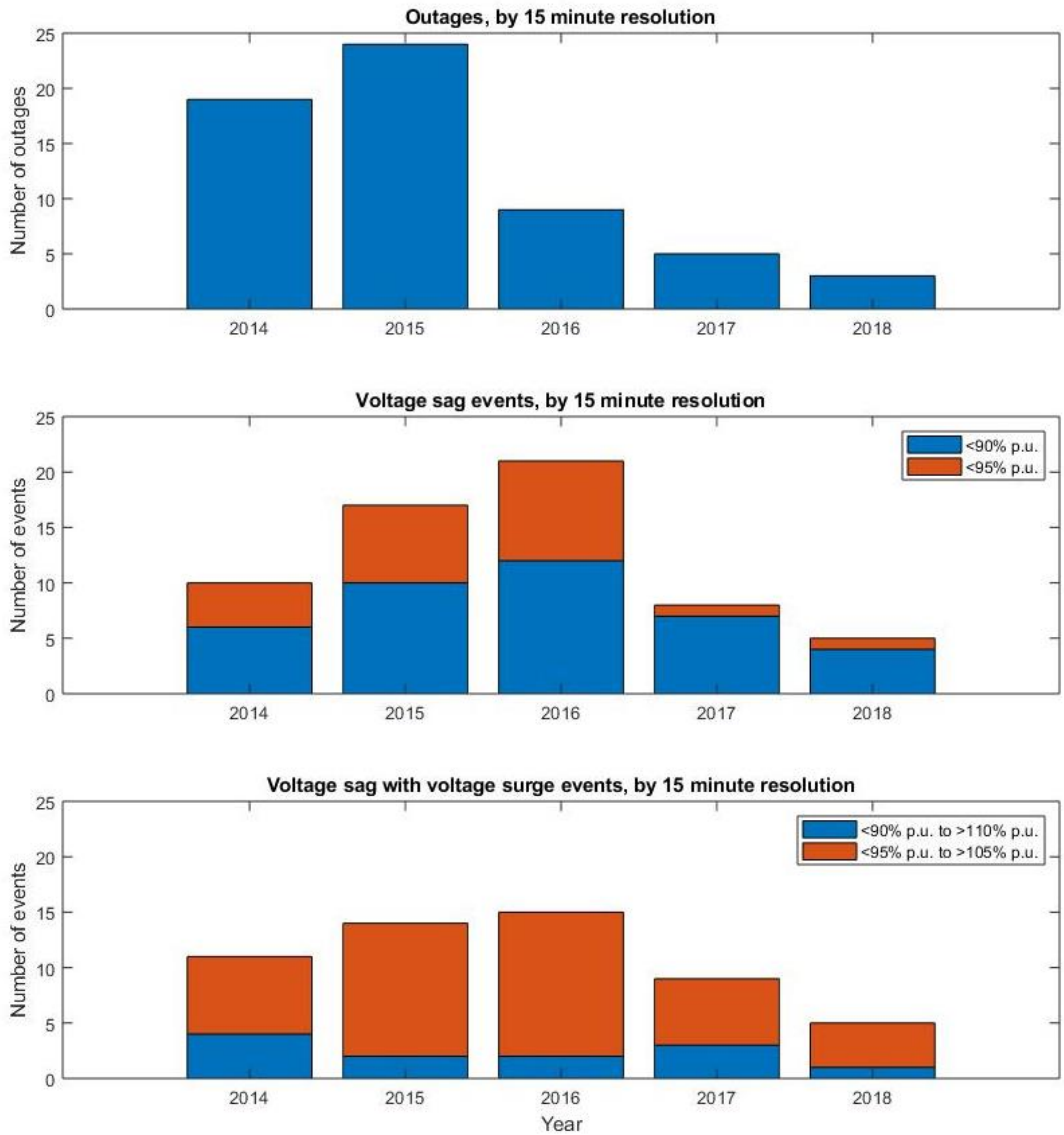

Figure 3: Medium Voltage Power Quality Events. The number of power quality events has decreased in years since the heat pumps were installed. Note the 2018 data cut-off is June 7, and therefore does not compare equally to other years.

The number of 15-minute periods with outages increases slightly from 2014 to 2015, then drops significantly in 2016 with gradual decreases in 2017. The number of 15-minute periods with voltage sag events (not including an outage) increase annually from 2014 to 2016, before dropping significantly in 2017. In the assessed period of 2018, voltage sag events have also decreased, but it is unclear whether they will end higher than in 2017 when data for the full year is available. The voltage sag with voltage surge event was assessed to evaluate the scenario where the generators respond to a voltage sag by ramping up too much causing voltage overshoot. The number of events with a minimum voltage below 90% p.u. and above 110% p.u. is low in every year, and no clear trends exist for whether they are decreasing over time. The number of events with a minimum voltage below 95% p.u. and above 105% p.u. increases from 2014 to 2016, then decreases in 2017. It is unclear whether these events will end higher than in 2017 when data for the full year is available. Appendix A shows power quality events broken out by month.

This data suggests that power quality metrics that may be affected by the heat pumps, when measured at the medium voltage level, have actually improved since the heat pump installations. This is not attributed to the heat pump installation, and it cannot be ruled out that the heat pumps have caused some of the remaining medium voltage power quality events. However, it does indicate that any medium voltage power quality events are likely to be very infrequent when compared to other sources of power quality issues.

Skidegate Low Voltage Monitoring

Isolated transient voltage sags at low voltage may not be visible at the medium voltage level. To determine whether the heat pumps are causing low voltage power quality issues, household level power quality meters have been installed on three representative households. Data is not yet available for analysis at the time of this report and will be assessed by BC Hydro's Power Quality group.

Conclusion

A statistical analysis of electricity consumption data before and after the heat pump installations indicates that the average household provided with a heat pump rebate decreased their electricity consumption by 413 kWh per year, or 2.9% of annual consumption. Due to anecdotal reports that many households significantly reduced their reliance on supplemental fuel sources such as fuel oil and wood, some households may have actually increased their electricity consumption. Households with no or little supplemental fuel use before heat pump installations may have therefore decreased their electricity consumption by more than the average of 2.9%. A subset analysis of this topic was not conducted due to lack of data availability and time constraints. If the rebate program intent is solely to drive electricity savings, future rebate programs could consider evaluating supplemental heating use from applicants and/or incentivizing a "whole home" approach to retrofits that emphasizes the need for building envelope improvements (e.g., air sealing and insulation) alongside the installation of efficient heating systems. If the rebate goal is to incentivize energy conservation from all sources, decrease overall energy costs, decrease GHG emissions, or improve heating quality and home comfort, then other evaluation criteria are required. The Skidegate installations were not able to be evaluated against these potential goals as insufficient data exists. A survey was prepared in conjunction with the Skidegate Band Council in an attempt to gain additional insight in these areas; however results are not yet available.

The impact of the heat pump installations in Skidegate on power quality was evaluated. Ductless heat pumps, which make up at least 87% of the installations, have starting currents approximately equal to refrigerator starting currents, and are therefore unlikely to contribute to power quality issues. Central heat pumps have relatively high starting currents but make up less than 13% of installations. Analysis of medium voltage power quality shows that power quality issues have decreased since the heat pumps have been installed, therefore it is likely that with the low penetration of these central heat pumps their impact on medium voltage power quality is negligible. Some power quality issues may not be detectable from the medium voltage data. Low voltage power quality meters were installed at three locations in Skidegate, and results will be available in the fall.

References

Environment and Climate Change Canada. *Sandspit Weather Data*. http://www.climate.weather.gc.ca. Accessed 4 July 2017.

Larson, Ben, et al. "Is Your Refrigerator Running? Energy Use and Load Shapes for Major Household Appliances." *ACEEE Summer Study on Energy Efficiency in Buildings*, 2014, pp. 235–46.

Appendix A Monthly Power Quality Events

This section contains more detailed graphs of the power quality events shown in Figure 3, organized by month.

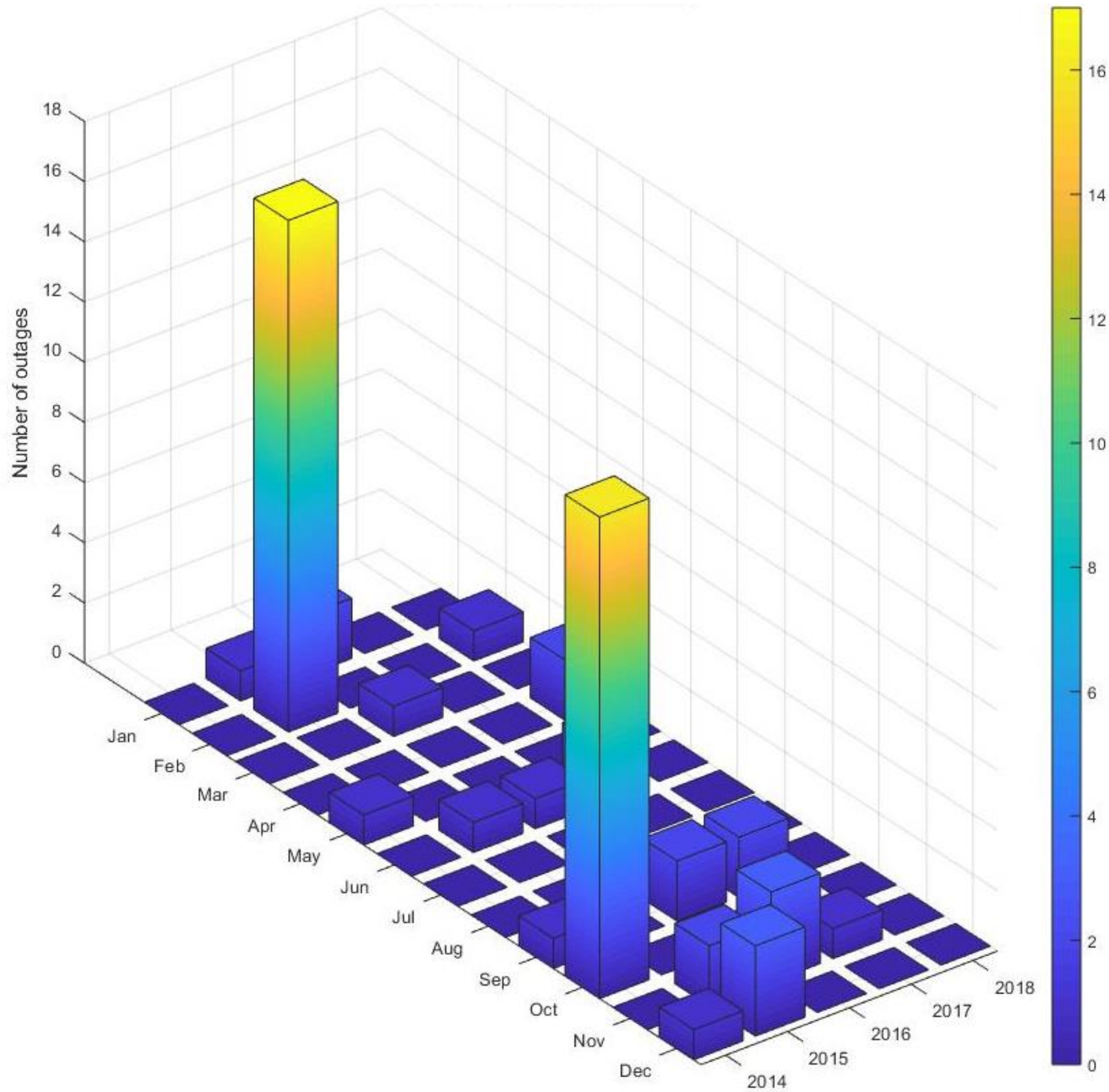

Figure A-4: Medium voltage outages by 15-minute resolution.

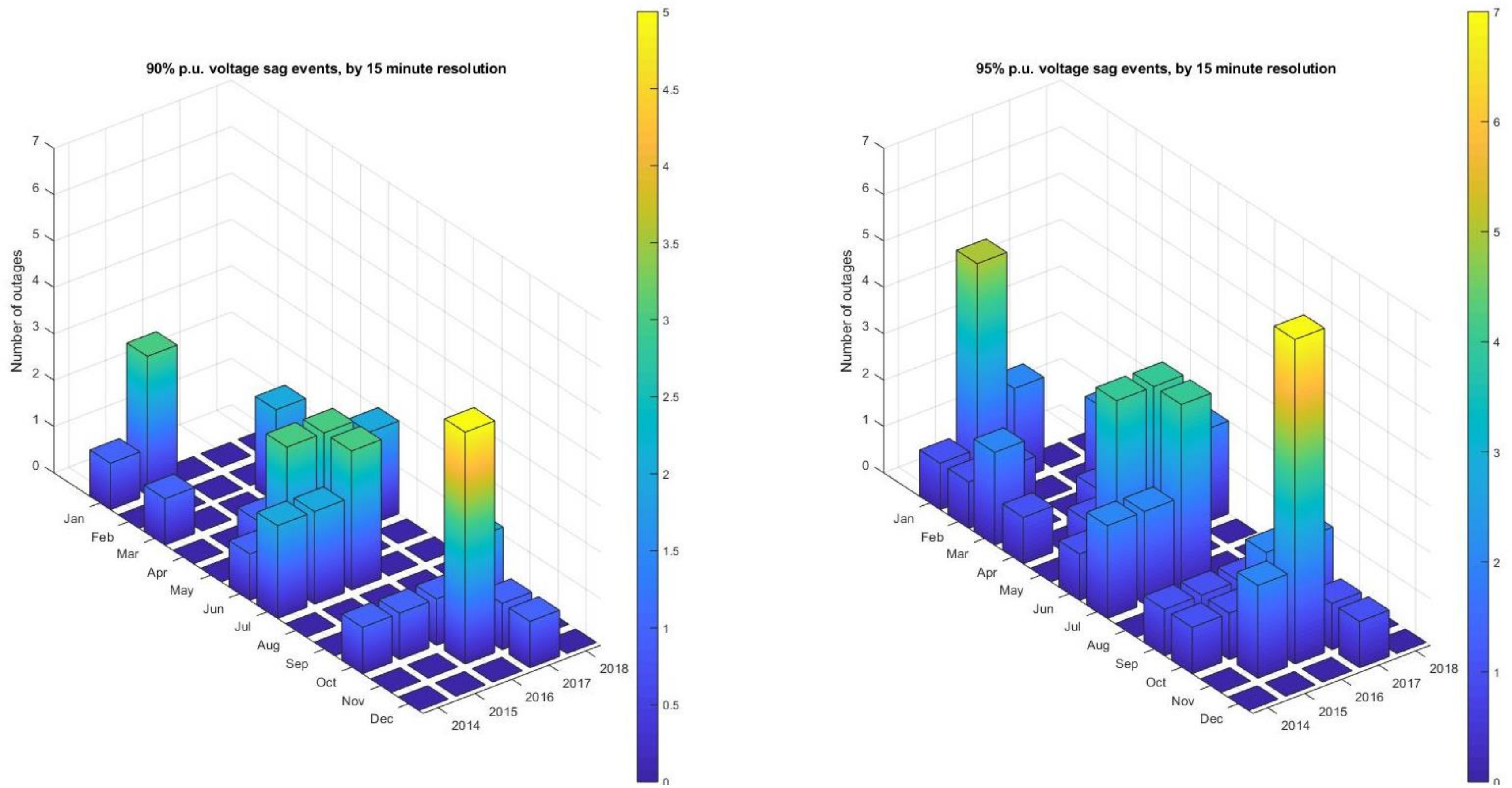

Figure A-5: 15-minute periods with a voltage sag

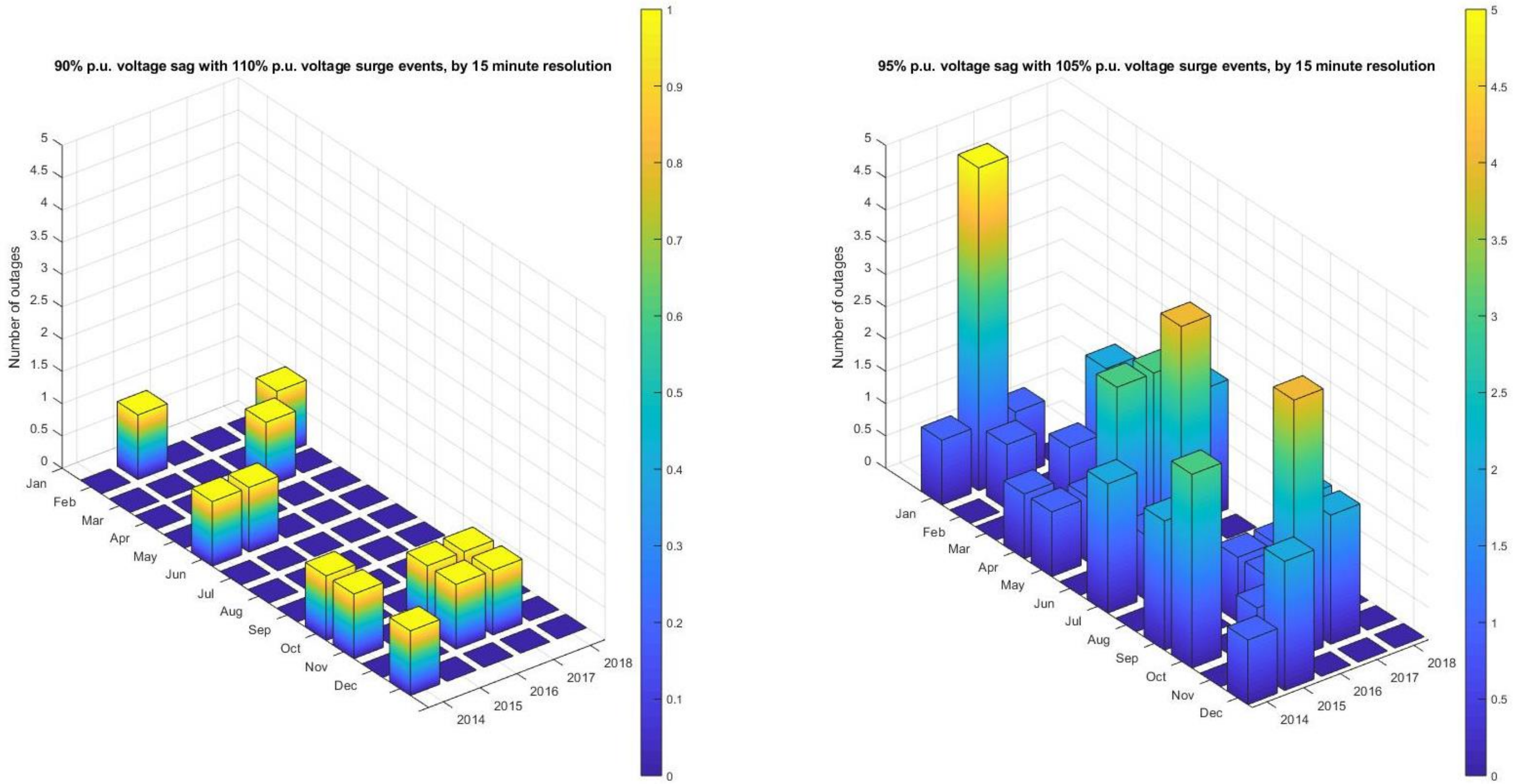

Figure A-6: 15-minute periods with a voltage sag and voltage surge