Impact of Temperature on Electricity Consumption Pattern in Alberta, Canada

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1.0 Introduction

This report outlines the data handling, analysis, and visualization techniques used to assess how temperature fluctuations, particularly extreme summer and winter conditions affect electricity consumption across nine distinct Alberta Electric System Operator (AESO) regions. The analysis spans data from 2011 to 2018.

1.1 Data Preparation

1.1.1 Data Import and Cleaning

Importing Data

The data imported included:

- **Population Data**: which contains annual municipal population counts.
- **Electricity Consumption Data**: which includes hourly consumption metrics by AESO district.
- **Dictionary Data**: This contains dictionaries for linking municipalities to AESO regions. Used to merge the datasets by geographic region. Contains Area ID and their respective district names and municipalities codes.
- **Shapefile Data**: contains geographic data for AESO regions.

Joining Population and Dictionary Data

- I merged the population data with the dictionary data by Area ID and year. This join is necessary as it maps the population data to specific AESO regions for accurate aggregation.
- The possible many-to-many join complexities that may arise were resolved by ensuring that each municipality correctly corresponds to its respective AESO region.

Aggregating Population Data

- After successfully joining, I aggregated population data by AESO Area ID and year. I achieved this by summing up population counts to get a total for each region per year.
- I cleaned the data by removing rows with NA values to ensure the dataset contains only complete cases for accurate analysis.

Importing and Preparing Temperature Data

- I imported temperature data for each district/region separately and then combine all into one Data Frame.
- The data in the temperature data frame was converted from wide to long format.
- I standardized the format of datetime columns of the temperature data, extracted necessary time components like year and month, then merged the time component to the temperature dataset.

Transforming and Merging Electricity Data

- I renamed the electricity data columns to match Area ID format and reshaped the data to long format for easier merging with other datasets.
- I also extracted the year from datetime for consistent temporal analysis across datasets.

Merging Population, Electricity Data, and Temperature data

- I joined the transformed electricity data with aggregated population data on 'Area ID' and 'year'. I calculated and merged another column for per capita electricity consumption to the joined dataset.
- I then joined the temperature data with the combined dataset from above using 'Area ID', 'year', and 'datetime' as keys

Final Data Cleaning Steps

- After all joins, I further cleaned the combined dataset by dropping any remaining rows with NA values to maintain data quality.

1.2 Visualization Strategy

Spatial and temporal data visualizations were planned to identify patterns:

- **Maps**: Using **sf** and **ggplot2**, I plotted a map of AESO regions, showing variations in electricity consumption and temperature across regions.

- **Time series and bar graphs**: Used to illustrate trends in temperature and electricity usage over the years and assess seasonal impacts.

1.3 Econometric Analysis

- I checked for the impact of seasonal temperature (winter and summer) on electricity usage by region.
- I applied regression analysis to investigate how extremes in temperature (by season) affect electricity usage.
- I investigated how July temperature spike impacted electricity consumption as well as how December cold snaps impacted electricity consumption by region.
- I also investigated how overall summer temperature and winter temperature impacted electricity consumption.
- The data was logged to normalize distribution and stabilize variance for the summer season. The log transformation wasn't applied to the winter model because it is not a good practice to log transform variables with negative values.

2.0 Results

2.1Visual description of average summer temperature and electricity consumption per capita

Figure 1 and Figure 2 are maps showing the average summer temperature and electricity consumption per capita, respectively. On the map, Area ID54 (Lethbridge) and 47 (Brooks) are observed to be the hottest region (17 - 18°C) on the summer temperature map. While Brooks (47) has high electricity consumption per capita (0.004Kwh) on the electricity consumption map, Lethbridge (54) show lower electricity consumption per capita (<0.001Kwh). Area ID29 (Hinton) is observed to have a lower (cooler) temperature (14 – 15°C) and higher per capita electricity consumption (≈ 0.004KWh). This is indicative of higher heating needs. Area IDs18 (Lethbridge), 27 (Athabasca), 40 (Wabamun), and 56 (Vegreville) are observed to have a mid-range temperature (≈ 16°C). Among these regions, 18, 27, 56 have a low temperature consumption per capita (≈ 0.002KWh) while 40 has even lower (≈ 0.001KWh) electricity consumption per capita. These results do not really show a definite per capita consumption of electricity in the summer indicating that there might be other factors influencing electricity consumption in these regions. These results are also supported by the bar graphs shown in Figure 3 and 4

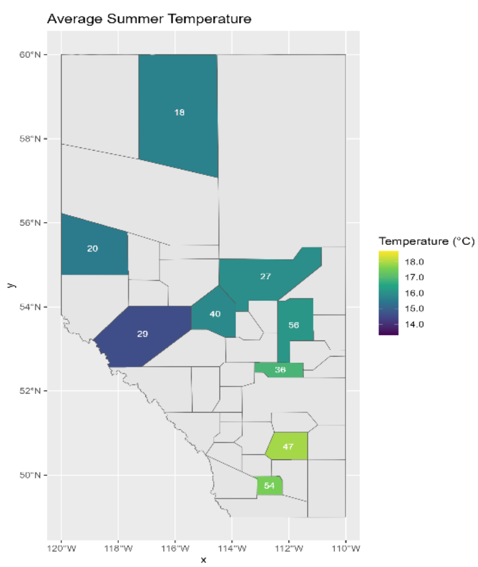


Fig1. Average summer temperature (map)

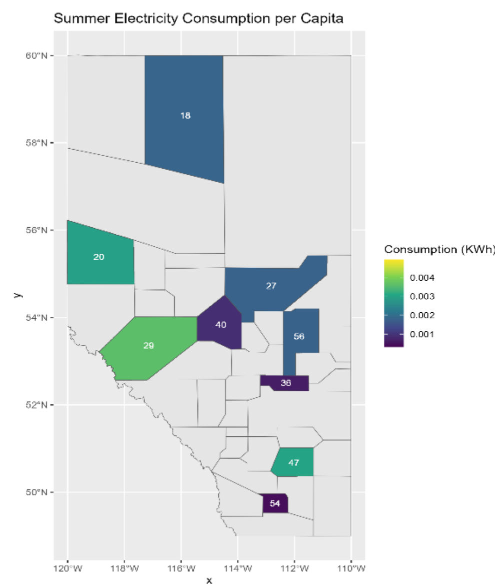


Fig2. summer electricity consumption per capita (map)

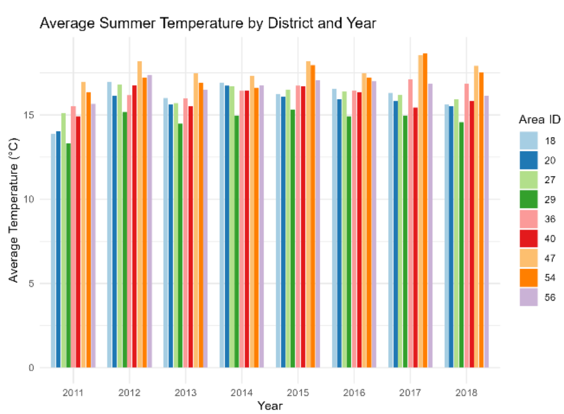


Fig3. Average summer temperature (bar graph)

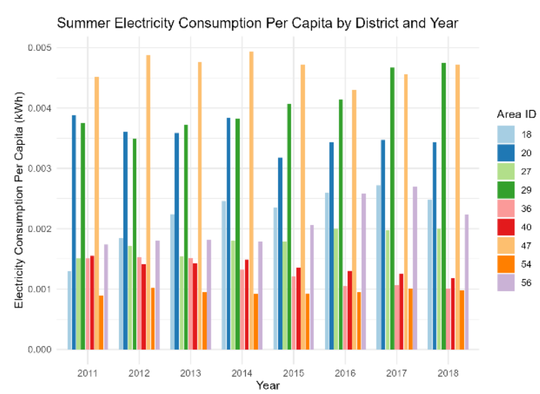


Fig4. summer electricity consumption per capita (bar graph)

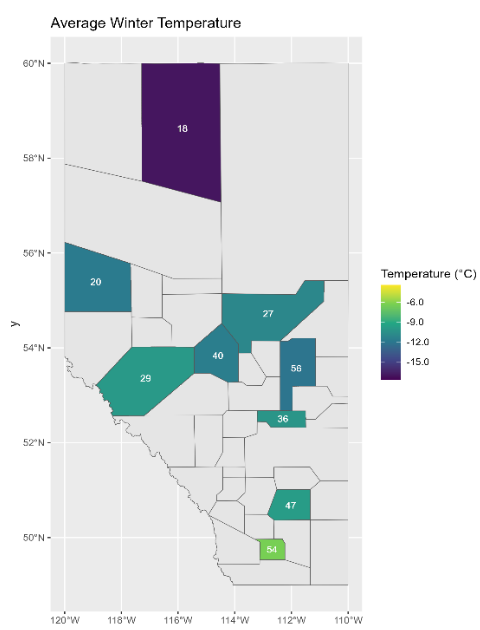
2.2 Visual description of average winter temperature and electricity consumption per capita

The Area IDs 20, 40, and 56 are seen to have a colder temperature of (≈ -12°C). Among these regions, region 20 is observed to have higher electricity consumption per capita (≈ 0.003KWh), region 56 has moderate electricity consumption per capita (0.002 – 0.00025KWh), and region 20 with a low electricity consumption per capita (0.001 – 0.00015KWh).

Regions 27, 29, 36, and 47 are observed to have a temperature of (≈ -10 to -9°C). Among these regions, region 36 have lower electricity consumption per capita (≈ 0.001KWh) and region 29 has a higher electricity consumption per capita (0.0035 – 0.004KWh)

Region 54 has a less cold temperature of (≈ -7°C) and a lower per capita electricity consumption of around <0.001KWh. Region 18 which appears to be the coldest region with a average temperature of around -15°C or lower has a low to moderate per capita electricity consumption of around 0.0015 – 0.002KWh.

These results do not follow a consistent pattern sufficient to draw a relationship between temperature and electricity consumption in the winter indicating that there might be other factors influencing electricity consumption in these regions. These results are also supported by the bar graphs shown in Figure 7 and 8



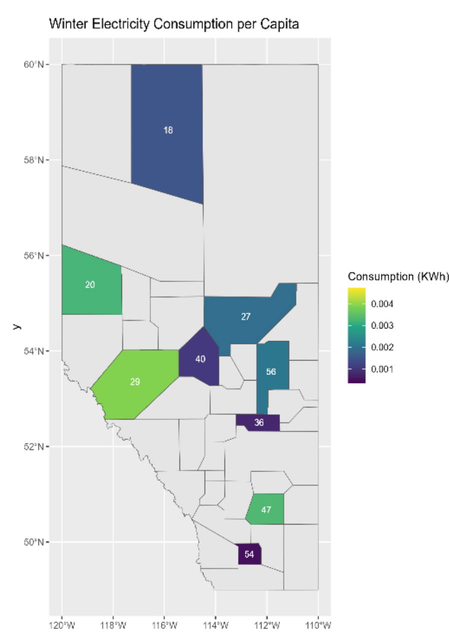


Fig5. Average winter temperature (map)

Fig6. Winter electricity consumption per capita (map)

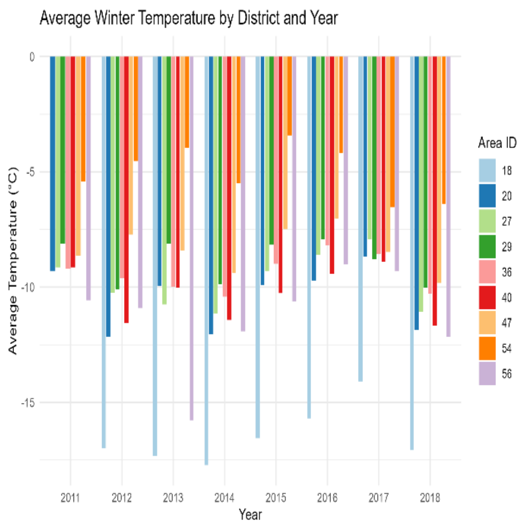


Fig7. Average winter temperature (bar graph)

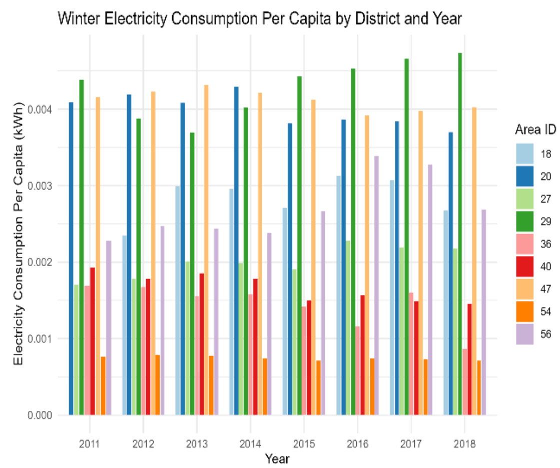


Fig8. Winter electricity consumption per capita (bar graph)

2.3 The effect of July temperature spikes on regional daily electricity consumption

Figure 9 presents the regression estimates of the effect of July temperature spikes on daily electricity consumption. The model's adjusted R squared is 0.8252 indicating that the predictors (daily maximum temperature, regions, and years) account for 82.5% variation in the model. The coefficient of the predictor of interest log(daily_max_temp) is 0.310 and is statistically significant ($p < 0.001$), indicating a positive and significant relationship between daily maximum temperature and per capita electricity consumption. This implies a 10% increase in maximum daily temperature in July will result in 3.1% increase in per capita electricity consumption on average.

Regions including Grande Prairie (Area ID20), Hinton (Area ID29) and Brooks (Area ID47) show significant positive coefficients with electricity consumption. This indicates that these regions experience higher electricity consumption with temperature spikes compared to the base region (High Level – Area ID18). On the other hand, regions including Alliance (Area ID36), Wabamun (Area ID40), Lethbridge (Area ID54), and Vegreville (Area ID 56) show significant negative relationship with electricity consumption. This indicates that these regions experience lower electricity consumption with temperature spikes compared to High Level.

For year, only 2013 showed a significant relationship with per capita electricity consumption relative to the reference year (2011). This relationship is negative and suggests that lower electricity per capita is consumed in 2013 compared to 2011.

```
Call:
lm(formula = log(daily_pc_consumption) ~ log(daily_max_temp) +
    Area_ID + year, data = july_summary)

Residuals:
    Min      1Q  Median      3Q     Max
-3.5526 -0.0827  0.0216  0.1191  0.5446

Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)         -4.274948   0.111219 -38.437  < 2e-16 ***
log(daily_max_temp)  0.310324   0.035316   8.787  < 2e-16 ***
Area_ID20            0.731737   0.025916  28.235  < 2e-16 ***
Area_ID27           -0.004217   0.025864  -0.163   0.8705
Area_ID29            0.790962   0.026074  30.335  < 2e-16 ***
Area_ID36           -0.470982   0.025864 -18.210  < 2e-16 ***
Area_ID40           -0.367484   0.026008 -14.129  < 2e-16 ***
Area_ID47            0.872091   0.026184  33.306  < 2e-16 ***
Area_ID54           -0.964943   0.026112 -36.955  < 2e-16 ***
Area_ID56           -0.144051   0.026181  -5.502 4.20e-08 ***
year2012            -0.035072   0.024882  -1.410   0.1588
year2013            -0.102338   0.024672  -4.148 3.49e-05 ***
year2014            -0.017626   0.024909  -0.708   0.4792
year2015            -0.047225   0.024714  -1.911   0.0562 .
year2016             0.016662   0.024486   0.680   0.4963
year2017             0.030672   0.024988   1.227   0.2198
year2018            -0.022746   0.024577  -0.926   0.3548
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.2768 on 2159 degrees of freedom
Multiple R-squared:  0.8264,    Adjusted R-squared:  0.8252
F-statistic: 642.5 on 16 and 2159 DF,  p-value: < 2.2e-16
```

Figure 9. The effect of July temperature spikes on regional daily electricity consumption

2.4 The effect of summer temperature spike on regional daily electricity consumption

Figure 10 presents the regression estimates of the effect of summer temperature spike on regional daily electricity consumption. The model's adjusted R squared is 0.8566 indicating that the predictors (daily maximum temperature, regions, and years) account for 85.7% variation in the model. The coefficient of the predictor of interest log(daily_max_temp) is 0.5547 and is statistically significant ($p < 0.001$), indicating a positive and significant relationship between daily maximum temperature and per capita electricity consumption in summer. This implies a 10% increase in maximum daily temperature in summer will result in 5.5% increase in per capita electricity consumption on average.

Regions including Grande Prairie (Area ID20), Hinton (Area ID29) and Brooks (Area ID47) show significant positive relationship ($p < 0.001$) with electricity consumption per capita. This indicates that these regions experience higher electricity consumption with temperature spikes compared to the base region (High Level – Area ID18). On the other hand, regions including Alliance (Area ID36), Wabamun (Area ID40), Lethbridge (Area ID54), and Vegreville (Area ID 56) show significant negative relationship ($p < 0.001$) with electricity consumption. This indicates that these regions experience lower electricity consumption with temperature spikes compared to High Level.

For year, 2013 showed a significant negative relationship ($p < 0.001$) with per capita electricity consumption relative to the reference year (2011). This indicates that lower electricity per capita is consumed in 2013 compared to 2011. Year 2016 also showed a significant positive relationship ($p < 0.05$). with per capita electricity consumption relative to the reference year. This indicates that higher electricity per capita is consumed in 2016 compared to 2011.

```
Call:
lm(formula = log(daily_pc_consumption) ~ log(daily_max_temp) +
    Area_ID + year, data = summer_summary)

Residuals:
    Min      1Q  Median      3Q     Max
-4.4138 -0.0721  0.0198  0.1150  0.5752

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)         -4.03664    0.15907 -25.376  < 2e-16 ***
log(daily_max_temp)  0.55467    0.04931  11.248  < 2e-16 ***
Area_ID20            0.73075    0.02315  31.567  < 2e-16 ***
Area_ID27            0.01091    0.02311   0.472 0.637021
Area_ID29            0.81143    0.02323  34.932  < 2e-16 ***
Area_ID36           -0.50044    0.02311 -21.655  < 2e-16 ***
Area_ID40           -0.39039    0.02307 -16.920  < 2e-16 ***
Area_ID47            0.81379    0.02369  34.356  < 2e-16 ***
Area_ID54           -1.03093    0.02355 -43.776  < 2e-16 ***
Area_ID56           -0.13743    0.02307  -5.957 2.98e-09 ***
year2012            -0.01579    0.02204  -0.716 0.473778
year2013            -0.08421    0.02174  -3.873 0.000111 ***
year2014             0.01154    0.02209   0.523 0.601372
year2015            -0.02466    0.02213  -1.114 0.265403
year2016             0.04853    0.02175   2.232 0.025740 *
year2017             0.01978    0.02200   0.899 0.368528
year2018            -0.02565    0.02229  -1.151 0.249999
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.2483 on 2187 degrees of freedom
Multiple R-squared:  0.8576,	Adjusted R-squared:  0.8566
F-statistic: 823.3 on 16 and 2187 DF,  p-value: < 2.2e-16
```

Figure 10. The effect of summer temperature spikes on regional daily electricity consumption

2.5 The effect of December cold snap on regional daily electricity consumption

The regression result of the effect of December cold snaps on regional daily temperature is presented in figure 11. The model's adjusted R squared is 0.9389 indicating that the predictors (daily maximum temperature, regions, and years) account for 93.4% variation in the model The coefficient of the predictor of interest (minimum daily temperature) is -0.0001112 and statistically significant, indicating that the per capita electricity consumption decreases by 0.0001112 units (KWh) for every degree Celsius decrease in temperature. This finding seems counterintuitive because colder temperatures are typically associated with increased heating demands, hence higher electricity consumption.

Regions including Grande Prairie (Area ID20), Hinton (Area ID29) and Brooks (Area ID47) show significant positive relationship ($p < 0.001$) with electricity consumption per capita. This indicates that these regions experience higher electricity consumption with temperature snap in December compared to the base region (High Level – Area ID18). On the other hand, regions including Alliance (Area ID36), Wabamun (Area ID40), Lethbridge (Area ID54), and Vegreville (Area ID 56) show significant negative relationship ($p < 0.001$) with electricity consumption. This indicates that these regions experience lower electricity consumption with temperature snap in December compared to High Level.

For year, 2016 and 2017 showed a significant positive relationship ($p < 0.001$) with per capita electricity consumption relative to the reference year (2011). This indicates that higher electricity per capita is consumed in these two years compared to 2011. Year 2018 however showed a significant negative relationship ($p < 0.05$) with per capita electricity consumption relative to the reference year. This indicates that lower electricity per capita is consumed in 2018 compared to 2011.

```
Call:
lm(formula = daily_pc_consumption ~ daily_min_temp + Area_ID +
    year, data = december_min)

Residuals:
      Min        1Q    Median        3Q       Max
-0.065335 -0.003843  0.000035  0.004191  0.020376

Coefficients:
                 Estimate Std. Error t value Pr(>|t|)
(Intercept)     4.483e-02  7.179e-04  62.451  < 2e-16 ***
daily_min_temp -1.112e-04  1.879e-05  -5.918 3.79e-09 ***
Area_ID20       3.691e-02  6.403e-04  57.650  < 2e-16 ***
Area_ID27      -5.529e-03  6.473e-04  -8.541  < 2e-16 ***
Area_ID29       4.057e-02  6.438e-04  63.015  < 2e-16 ***
Area_ID36      -2.109e-02  6.483e-04 -32.524  < 2e-16 ***
Area_ID40      -1.643e-02  6.636e-04 -24.763  < 2e-16 ***
Area_ID47       3.812e-02  6.478e-04  58.843  < 2e-16 ***
Area_ID54      -3.358e-02  6.643e-04 -50.549  < 2e-16 ***
Area_ID56      -3.111e-05  6.430e-04  -0.048 0.961420
year2012       -9.612e-04  6.270e-04  -1.533 0.125450
year2013        2.266e-04  6.262e-04   0.362 0.717546
year2014       -7.195e-04  5.995e-04  -1.200 0.230203
year2015       -8.563e-04  6.001e-04  -1.427 0.153734
year2016        2.285e-03  6.132e-04   3.727 0.000199 ***
year2017        3.035e-03  6.208e-04   4.889 1.09e-06 ***
year2018       -1.384e-03  5.967e-04  -2.319 0.020468 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.006784 on 2149 degrees of freedom
Multiple R-squared:  0.9394,	Adjusted R-squared:  0.9389
F-statistic:  2082 on 16 and 2149 DF,  p-value: < 2.2e-16
```

Figure 11. The effect of December cold snap on regional daily electricity consumption

2.6 The effect of winter cold snap on regional daily electricity consumption

The regression result of the effect of winter cold snaps on regional daily temperature is presented in figure 12. The model’s adjusted R squared is 0.8987 indicating that the predictors (daily maximum temperature, regions, and years) account for 89.9%% variation in the model The coefficient of the predictor of interest (minimum daily temperature) is -0.0003557 and statistically significant, indicating that the per capita electricity consumption decreases by 0.0003557 units (KWh) for every degree Celsius decrease in temperature. This finding seems counterintuitive because colder temperatures are typically associated with increased heating demands, hence higher electricity consumption.

Regions including Grande Prairie (Area ID20), Hinton (Area ID29) and Brooks (Area ID47) show significant positive relationship ($p < 0.001$) with electricity consumption per capita. This indicates that these regions experience higher electricity consumption with temperature snap in winter compared to the base region (High Level – Area ID18). On the other hand, regions including Alliance (Area ID36), Wabamun (Area ID40), Lethbridge (Area ID54), and Vegreville (Area ID 56) show significant negative relationship ($p < 0.001$) with electricity consumption. This indicates that these regions experience lower electricity consumption with temperature snap in winter compared to High Level.

For years, 2014, 2016, and 2017 showed a significant positive relationship at ($p<0.05$), ($p < 0.001$) and ($p<0.01$), respectively with per capita electricity consumption relative to the reference year (2011). This indicates that higher electricity per capita is consumed in these three years compared to 2011. Year 2013 however showed a significant negative relationship ($p < 0.001$) with per capita electricity consumption relative to the reference year. This indicates that lower electricity per capita is consumed in 2013 compared to 2011.

```
Call:
lm(formula = daily_pc_consumption ~ daily_min_temp + Area_ID +
    year, data = winter_summary)

Residuals:
      Min        1Q    Median        3Q       Max
-0.099662 -0.009802  0.003893  0.016900  0.053690

Coefficients:
                Estimate Std. Error t value Pr(>|t|)
(Intercept)     1.185e-01  3.419e-03  34.655  < 2e-16 ***
daily_min_temp -3.557e-04  7.926e-05  -4.487 7.59e-06 ***
Area_ID20       1.106e-01  2.459e-03  44.967  < 2e-16 ***
Area_ID27      -1.539e-02  2.485e-03  -6.195 6.95e-10 ***
Area_ID29       1.256e-01  2.483e-03  50.566  < 2e-16 ***
Area_ID36      -5.098e-02  2.480e-03 -20.562  < 2e-16 ***
Area_ID40      -4.743e-02  2.468e-03 -19.216  < 2e-16 ***
Area_ID47       1.197e-01  2.475e-03  48.382  < 2e-16 ***
Area_ID54      -9.002e-02  2.535e-03 -35.503  < 2e-16 ***
Area_ID56      -4.755e-03  2.457e-03  -1.935 0.053081 .
year2012       -3.970e-03  2.290e-03  -1.734 0.083127 .
year2013       -8.143e-03  2.294e-03  -3.550 0.000394 ***
year2014        5.742e-03  2.289e-03   2.509 0.012177 *
year2015       -3.115e-03  2.296e-03  -1.357 0.174972
year2016        1.088e-02  2.306e-03   4.718 2.53e-06 ***
year2017        6.718e-03  2.295e-03   2.927 0.003453 **
year2018        2.342e-03  2.288e-03   1.023 0.306232
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.02611 on 2184 degrees of freedom
Multiple R-squared:  0.8994,    Adjusted R-squared:  0.8987
F-statistic:  1221 on 16 and 2184 DF,  p-value: < 2.2e-16
```

Figure 12. The effect of winter cold snap on regional daily electricity consumption