The Impact of Climate Change on Singapore's Future Electricity Demand Based on a Multivariate Approach

Projecting Singapore's Electricity Usage in 2050

SMTP Math Research Paper
Project Work Final Written Report

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Abstract

As global warming intensifies, future electricity demand/consumption is likely to see an increase as households and businesses try to adapt to the rising temperatures by increasing cooling measures. Various statistical researches have been conducted in the past and these have shown that the magnitude of increase in electricity consumption is strongly linked to climate change factors and socioeconomic factors. An understanding of these factors' impact on electricity demand/consumption is therefore essential for public mitigation and adaptation policies. While many studies are focused on the statistical relationships between climate and socioeconomic factors, there is a lack of a predictive component in many of the electricity consumption and weather studies, especially for Singapore's context. Therefore, the purpose of our research is to investigate how electricity consumption is statistically related to Singapore's socioeconomic and climate variables and also to predict the impact of climate changes on Singapore's electricity consumption and prices in 2050 based on the Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 climate change scenarios for Singapore. Using single-variable and multivariate regressions with backward elimination procedure, we first establish the statistical relationships between electricity consumption and key socioeconomic and climate variables in Singapore. Based on the regression results, mathematical models are formulated to predict the electricity consumption in 2050. Our analysis shows that Total Electricity Consumption only correlates with Gross Domestic Product (GDP) and Median Monthly Household Income in the multivariate regression and Electricity Price is not

correlated with Total Electricity Consumption in all regressions. Total Electricity Consumption in 2050 is projected to be 73.9% above 2018 levels based on our mathematical model with GDP and Median Monthly Income. Our research also reveals that Singapore's Residential Electricity Consumption has significant correlation with both Average Monthly Household Income and Average Daily Temperature and hence climate change is likely to have a greater impact on Singapore's residential households than commercial/industrial entities. The increase in temperature is estimated to have a 1.8% to 6.5% impact on Singapore's residential electricity consumption in 2050 and residential electricity consumption in 2050 is expected to be 101.6% above 2018 levels in the worst case scenario for temperature increase. Given the significant increase in residential electricity consumption in 2050 due to climate change, further mitigation strategies need to be implemented to lessen the impact of the increase to a typical Singapore household.

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1) Introduction

1.1) Introduction and Rationale

As global warming intensifies, future electricity demand/consumption is likely to see an increase as households and businesses try to adapt to the rising temperatures by increasing cooling measures and other mitigation methods. In Singapore, from 2005 to 2016, the annual mean temperature increased from 28°C to 28.4°C. During this period, the consumption of electricity also increased from 35,489 GWh to 48,626 GWh. It is conceivable that climate change and the rise in temperature will have an impact on future electricity demand in Singapore.

Various statistical researches have been conducted in the past and these have shown that the magnitude of increase in electricity consumption is strongly linked to climate change factors and socioeconomic factors. An understanding of these factors' impact on electricity demand/consumption is therefore essential for public mitigation and adaptation policies. Such an impact will be a major concern for the Singapore Government, as it requires time to expand its capacity to generate more electricity in order to meet the future consumption. Moreover, as electricity usage increases, this will also impact the electricity prices in Singapore. However, research on the exact relationship between climate change and socioeconomic factors on electricity usage in Singapore are currently limited, and the exact relationships between the factors and electricity consumption are not clearly understood in Singapore.

Doshi, Rohatgi, Zahur and Hung (2013) studied the impact of climate change variables on electricity demand of Singapore using statistical analysis based on data sets from 2003 to 2012. Since 2012, Singapore has experienced 4 of the 10 warmest years, namely 2014, 2015, 2016, and 2019. With record temperatures and more extreme weather in the last 5 years in Singapore, it is thus more urgent to understand the relationship between climate change and electricity usage utilizing the latest climate data. Their study also did not provide a forecast of future electricity consumption in Singapore based on the statistical relationships established in their research. It is therefore useful to examine new socioeconomic and weather variables that are not included in the Doshi et al (2013) study, and provide a forecast of future electricity demand in Singapore based on these new insights.

Through single variable and multivariate statistical analysis with backward elimination procedure, this project aims to analyse how the electricity consumption in Singapore relates to weather variables such as temperature, humidity, PSI, sunshine hours, and rainy days. The future data for these weather variables will be based on two Representative Concentration Pathways (RCPs) 4.5 and 8.5 climate change scenarios for Singapore. These pathways span a plausible range of future global atmospheric global greenhouse gas (GHG) concentrations and are associated with varying levels of climate change. In addition to weather variables, the project will also investigate how the electricity demand relates to household income, population and national income.

Finally, based on the multivariate analysis of data, the project aims to create a mathematical model to predict electricity consumption and prices based on the weather and socioeconomic factors. For comparison, a "Base Case" scenario for electricity consumption in Singapore will be formulated to analyse the impact of climate change on electricity consumption in Singapore in 2050.

1.2) Objectives

The project aims to understand the relationships between key climate and socioeconomic factors with electricity consumption/demand in Singapore, and based on the relationships, further investigates the impact of climate change on Singapore's future electricity demand and prices using multivariate regression methods.

Specifically, the project will

- Investigate how the electricity demand/consumption in Singapore relates to socioeconomic factors such as the number of households, household income, population and national income etc;
- Analyse how the electricity demand/consumption in Singapore relates to weather variables such as temperature, number of hot days, humidity, cloud cover, PSI index and rainy days currently.
- Determine the multivariate relationships between climate change, socioeconomic variables with the electricity consumption in Singapore.
- Predict the impact of climate changes on electricity consumption and prices in Singapore in 2050 based on the RCP 4.5 and RCP 8.5 climate change scenarios.

1.3) Research Questions

Based on the objectives of the study, the following research questions are identified:

- What is the statistical relationship between socioeconomic variables and the total electricity consumption/demand in Singapore?
- What is the statistical relationship between climate variables and the total electricity consumption/demand in Singapore?
- What is the multivariate relationship between climate change, socioeconomic variables and the total electricity consumption in Singapore?
- What is the projected consumption for total electricity in Singapore in 2050 based on the RCP 4.5 and RCP 8.5 climate scenarios?

1.4) Fields of Mathematics

The main fields of Mathematics involved are as follows:

- Statistics
- Data science
- Probability
- Mathematical Modelling

2) Literature Review

Doshi, Rohatgi, Zahur and Hung (2013) studied the impact of climate change on electricity consumption of Singapore. To date, this is the only published study in Singapore which tried to explore the impact of climate variables on electricity consumption in Singapore using statistical methods. The study utilized econometric techniques to investigate the relationship between electricity consumption and climate variables, using historical data on both electricity consumption and temperature in Singapore. The data set used was based on 2003 to 2012. The study found that temperature changes have a positive impact on electricity consumption and there are greater temperature elasticities during the night than in the day, due to the fact that the residential load takes up a much bigger proportion of the electricity load at night. The amount of economic activity, measured by Gross Domestic Product (GDP), is also found to have a positive influence on Singapore's electricity consumption.

Doshi et al. (2013) study can be further expanded by looking at other socioeconomic and weather factors such as haze pollution, population change, household income and commercial/residential building growth. Since the research was published in 2013 (using data from 2002 to 2012), Singapore has experienced 4 of the 10 warmest years since 2012 (Chua 2019). The years were 2014, 2015, 2016, and 2019. A new study which incorporates Singapore's latest climate data can provide further insights on the relationship between climate change and electricity consumption. With record temperatures and more extreme weather in the last 5 years, it is more urgent to understand the relationship between climate change and electricity usage now. Lastly, while Doshi et al (2013) provided evidence of correlation between climate variables and electrical consumption, the study did not go further in extrapolating its findings on the impact of Singapore's future electrical consumption and prices. By incorporating Singapore's RCP 4.5 and RCP 8.5 scenarios in a statistical analysis, a more useful electricity consumption and price prediction model can certainly be created to assist Singapore policy makers in future electricity planning.

Given the attention to climate change in recent years, other international researchers have started to pay more attention to how the energy demand would grow due to global warming. Li, Pizer and Wu (2018) investigated the impact of +1 degree Celsius in the annual global mean surface temperature in China's Yangtze River Delta and found that the annual electricity consumption increases by 9.2%. Using the econometric approach, the study included household income as a variable during the investigation. After establishing the relationship between annual global mean surface temperature and electricity consumption, the study constructed a relationship between future annual global mean surface temperature changes in Shanghai region and annual residential electricity consumption.

Li, Cai, Chen, Chen, Zhang and Pan (2018) analysed the relationship between the weather variables and electricity load in Nanjing, China by establishing a mathematical model to analyse the effects of temperature changes on building energy consumption. The study noted that investigation on climate change on electricity demand has important practical significance to the study of urban carbon emission, future energy forecast and environmental air quality.

Chen (2017) examined the socioeconomic factors affecting residential electricity consumption in Taiwan and found that GDP, employment rates, residential space, and various energy efficiency schemes provide significant impacts on residential electricity consumption. Chen (2017) also analysed the impact of electricity prices on electrical consumption and found no significant correlation with residential electricity consumption. The study by Chen (2017) on the lack of significant correlation between electricity consumption and electricity prices coincides with the finding by Jamil and Ahmad (2010) where they found insignificant impact of electricity prices on electricity consumption in Pakistan.

In a more extensive study by Ruijven, Cian and Wing (2019), the researchers employed econometric methods to analyse the correlation between energy use and GDP, hot/cold days with future projections of population and national income in various geographical regions in the world. The study found that energy demand rises by more than 25% in the tropics and southern regions of the USA, Europe and China. Given that the study focused on regional economies, there is a limited usefulness for Singapore from the study as the results and implications are too generalized for Singapore.

The various research papers mentioned above point to the value of a top-down mathematical modelling of various weather and socioeconomic variables with electricity consumption in Singapore. According to Ruijven et al (2019), these top-down approaches are increasingly used in electricity demand studies as they are better at capturing global trends over the long run than bottom-up studies which typically simulate energy consumptions based on buildings or building archetypes. Moreover, bottom-up models also face the issue of technological and behavioural uncertainty which will result in greater complexity and data requirements, making it difficult to develop high-quality global bottom-up models.

The literature review here also highlighted a lack of a predictive component in many of the electricity consumption and weather studies, especially for Singapore's context. The majority of the studies reviewed here have focused on primarily the correlations of various factors with electricity consumption. Studies that focus on future projections of electricity consumption and price utilizing the various climate change scenarios are uncommon and can provide valuable insights to future demand scenarios to any policy decision makers.

3) Methodology/Procedure

3.1 Methodology

- Collect data (2005 to 2018) related to Singapore's:
  - Weather variables such as temperature, PMI, sunshine hours, and relative humidity etc;
  - Socioeconomic variables such as household income, population, GDP; and
  - Electricity demand/consumption and prices.
- Obtain the two Representative Concentration Pathways (RCPs) 4.5 and 8.5 climate change scenarios for Singapore in 2050.
- Determine the relationships between weather factors and electricity consumption using multivariate statistical analysis with backward elimination regression.

$$\mathbf{E_t = \beta_0 + \beta_1 T_t + \beta_2 HD_t + \beta_3 HU_t + \beta_4 SH_t + \beta_5 PSI_t + \beta_6 RD_t + L_t}$$

where E is the electricity consumption in Singapore;

β_0 is the intercept;

T is the annual mean daily temperature in Singapore;

HD is the annual number of hot days in Singapore;

HU is the annual mean humidity level in Singapore; and

SH is the daily sunshine hours in Singapore; and

PSI is the pollution index in Singapore;

RD is the number of raining days in Singapore; and

L_t is the dummy variable

- Determine the relationships between socioeconomic factors and electricity consumption using multivariate statistical analysis with backward elimination regression.

$$\mathbf{E_t = \partial_0 + \partial_1 GDP_t + \partial_2 HH_t + \partial_3 HI_t + \partial_4 PO_t + \partial_5 EP_t + D_t}$$

where E is the electricity consumption in Singapore;

∂_0 is the intercept;

GDP is the national income of Singapore;

HH is the number of households of Singapore;

HI is the median monthly household income of Singapore;

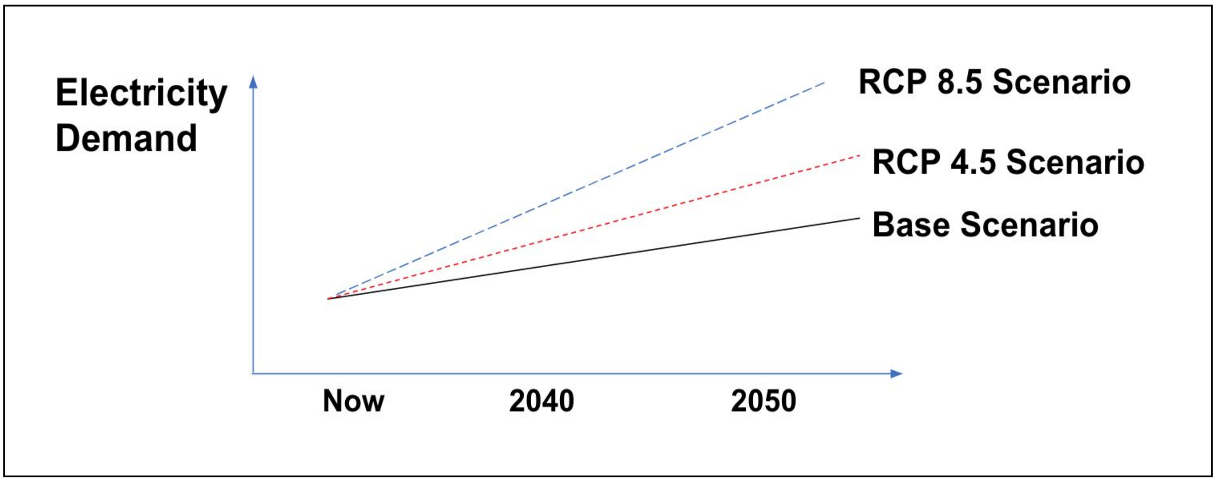
PO is the population of Singapore;

EP is the price of electricity in Singapore; and

D_t is the dummy variable.

- Predict the electricity consumption in Singapore in 2050 based on the mathematical models and statistical correlation under the Base Case, RCP 4.5 and RCP 8.5 scenarios as shown in Figure 1 below.

Figure 1: Electricity Consumption/Demand with Different Climate Scenarios



- To identify the possible implications of the impact of climate change on Singapore's electricity demand/consumption

3.2 Data Sources

Various data sources were collected from the below for this research:

1. Data.gov.sg:
    a. Singapore Annual GDP, Number of Households, Median Monthly Household Income, Electricity Prices and Population figures as shown in Table 1

Table 1: List of Socioeconomic Factors

Year	GDP (Million of S$)	Median Monthly Household Income (S$)	Population	Electricity Prices (¢ / kWh)	Number of Households
2005	212,723	4,831	4,265,762	21.40	1,024,500
2006	236,159	4,952	4,401,365	25.10	1,054,100
2007	272,698	5,362	4,588,599	23.50	1,074,800
2008	273,942	6,100	4,839,396	28.10	1,093,100
2009	282,395	6,006	4,987,573	22.60	1,119,600
2010	326,980	6,342	5,076,732	25.50	1,145,900
2011	351,368	7,037	5,183,688	27.60	1,146,200
2012	368,771	7,566	5,312,437	29.00	1,152,000
2013	384,870	7,872	5,399,162	26.80	1,174,500
2014	398,948	8,292	5,469,724	25.60	1,200,000
2015	423,444	8,666	5,535,002	21.60	1,225,300
2016	440,218	8,846	5,607,283	18.60	1,263,600
2017	472,079	9,023	5,612,253	20.10	1,289,900
2018	503,395	9,293	5,638,676	21.90	1,325,300

2. Dr Muhammad Eeqmal Hassim, Senior Research Scientist, Centre for Climate Research Singapore, Meteorological Service Singapore:
    a. RCP 4.5 and 8.5 Projections for Singapore
    b. Singapore's Climate Projection to 2100

Figure 2: Singapore Temperature Change based on RCP 4.5 and RCP 8.5

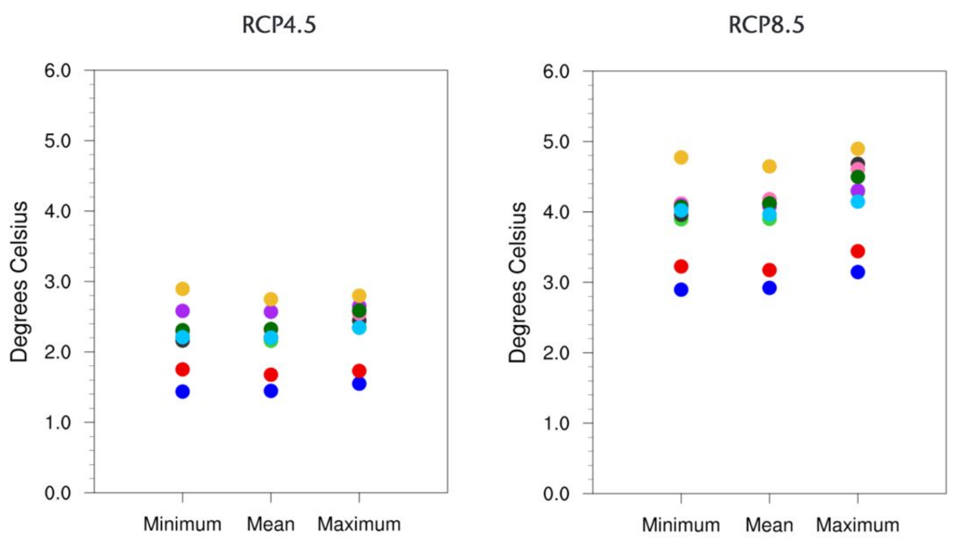


Figure 4.3: Change in average daily minimum, mean and maximum temperature for end-century (2070-2099) with respect to baseline period 1980-2009 for the RCP4.5 (left) and RCP8.5 (right).

		Mid-century (2040 - 2069)				End-century (2070 - 2099)			
Mean observed (1980 - 2009)		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
Minimum Temp (deg C)	24.1	25.4	26.4	25.9	27.1	25.5	27.0	27.0	28.9
Mean Temp (deg C)	27.4	28.7	29.6	29.2	30.3	28.8	30.1	30.3	32.0
Maximum Temp (deg C)	31.8	33.1	34.5	33.8	34.9	33.3	34.6	34.9	36.7

Table 4.1: Projected ranges in the average daily minimum, mean and maximum temperature for mid- and end-century for the RCP4.5 and RCP8.5 scenarios. The two values in each pair give the lower and upper range for each of the variables and these changes are statistically significant.

c. Annual Mean Daily Temperature, Annual Mean Relative Humidity level, Number of Raining Days, PSI index, Sunshine Hours as shown in Table 2 below:

Table 2: List of Climate Variables

Year	Annual Average Relative Humdity (%)	Average PSI Index PM 2.5	Average PSI Index PM 10	Average Daily Temperature (degree)	Monthly Avearge Sunshine Hours	Number of Rain Days
2005	0.831	21	61	28.01	6.067	175
2006	0.846	23	120	27.74	5.633	174
2007	0.845	19	53	27.54	5.317	195
2008	0.835	16	49	27.47	5.242	182
2009	0.824	19	59	27.93	5.950	166
2010	0.829	17	76	28.09	5.692	178
2011	0.845	17	55	27.57	5.575	188
2012	0.835	19	57	27.54	5.533	191
2013	0.817	20	215	27.65	5.433	206
2014	0.785	18	75	27.92	5.975	152
2015	0.769	24	186	28.24	6.167	125
2016	0.76	15	61	28.43	6.000	179
2017	0.826	14	57	27.70	5.800	204
2018	0.796	15	59	27.89	5.750	188

3. Energy Market Authority of Singapore

a. Total Electricity Consumption (include Commercial, Industrial and Residential consumption) and Residential Electricity Consumption as shown in Table 3 below. The data is only available from 2005 to 2018.

Table 3: Total and Residential Electricity Consumption

Year	Total Electricity Consumption (GWH)	Consumption Residential (GwH)
2005	35,489	6,092
2006	36,802	6,109
2007	38,305	6,164
2008	38,987	6,094
2009	38,823	6,431
2010	42,252	6,636
2011	43,007	6,483
2012	44,201	6,630
2013	44,949	6,755
2014	46,403	6,924
2015	47,514	7,221
2016	48,627	7,589
2017	49,644	7,296
2018	50,449	7,221

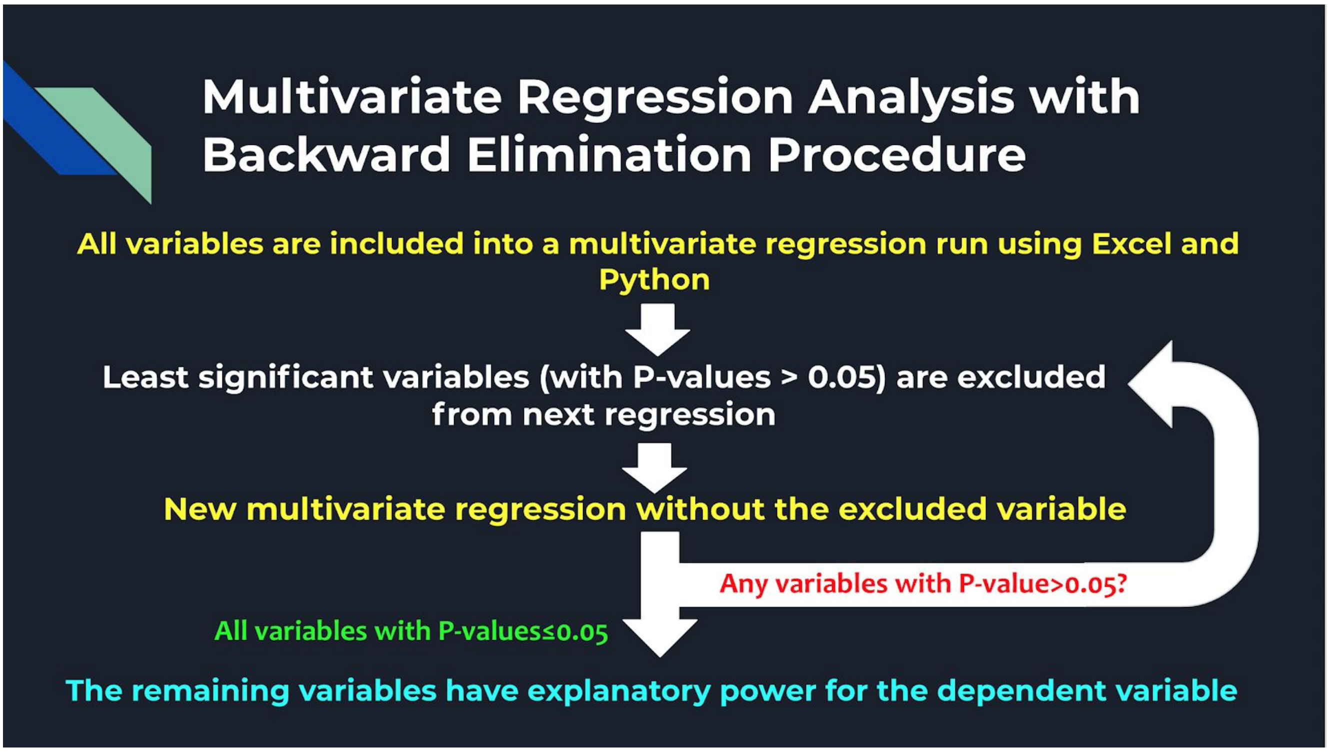
3.3 Regression Analysis

Regression analysis provides the connection between the independent and dependent variables and the degree of their correlation. To identify the mathematical relationships and/or statistical correlations between the various factors and electricity consumption, we have used the regression tools found in Excel and Python.

The significance of a variable in its relationship with electricity consumption in Singapore is investigated in the first step using single-variable regression. Following the single-variable regression, the backward elimination regression method is employed to exclude the insignificant variables in the multivariate regression analysis. At the start of the multivariate regression, all the variables are included into the regression. The least significant variable in the regression is then excluded from the subsequent regression through the application of backward elimination regression analysis. The probability criterion to exclude a variable from the model can be set as significance value more than 0.05. This means that in the regression analysis, a new model will be formed without the excluded variable. The process will continue until all the variables in the model have significant value less than 0.05 and the remaining variables are considered as the most significant variables affecting electricity consumption.

Figure 3 below shows the process of backward elimination in our multivariate regression.

Figure 3: Backward Elimination in Multivariate Regression



4) Results and Discussions

4.1 Research Question 1

<u>What is the statistical relationship between socioeconomic variables and the total electricity consumption in Singapore?</u>

For the first research question, we examined the significance of the Singapore socioeconomic variables/factors, such as Number of Households, Annual GDP, Median Household Income, Population and the Total Electricity Consumption in Singapore. These data are detailed in Table 1 in Section 3.2. We also examined the relationship between electricity prices and total electricity consumption in Singapore.

4.1.1 Single-Variable Regression Models

Using the regression tool in Excel and Python, the individual factors were analysed against Singapore's total electricity consumption from 2005 to 2018. The results of the various regression models are shown in Table 4 below.

Table 4: P-Values for Respective Independent Socioeconomic Variables (Single-Variable Regression Model)

Against Total Electricity Consumption					
	Number of Households	GDP	Median Monthly Household Income	Population	Electricity Prices
P-Values	1.52×10^{-9}	1.16×10^{-13}	1.30×10^{-11}	2.64×10^{-8}	0.287

Based on the criteria set for the P-values, the socioeconomic factors such as Number of Households, GDP, Median Monthly Household Income and Population show statistically significant correlation with Total Electricity Consumption in Singapore. The intercepts for the variables are also statistically significant. This means the independent socioeconomic variables are strongly correlated to the Total Electricity Consumption in Singapore based on the data set from 2005 to 2018 and can be useful in forecasting future consumption.

4.1.2 Multivariate Regression Models

Employing the backward elimination regression method to exclude the insignificant variables in the multivariate regression analysis, the socioeconomic factors that show statistical significance with total electricity consumption are detailed in Table 5.

Table 5: P-Values for Significant Socioeconomic Variables (Multivariate Variable Regression Model)

Against Total Electricity Consumption		
	Median Monthly Household Income	GDP
P-Values	0.027	2.8×10^{-4}

The multivariate regression results show only Median Monthly Household Income and GDP factors are significant factors in explaining the Total Electricity Consumption in Singapore.

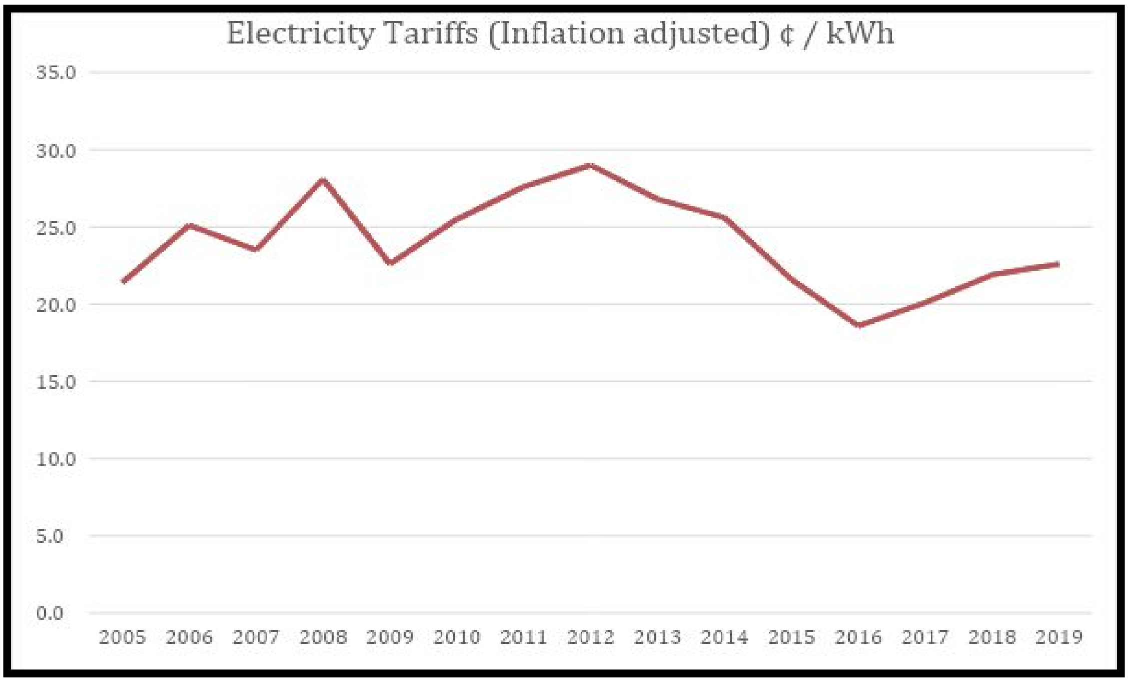
4.1.3 Discussions

The single variable regressions in Section 4.1.1 shows that the p-values of all socioeconomic factors used in the regression models are well within the 0.05 benchmark, except for electricity prices, This indicates that these socioeconomic factors are able to explain the growth in Total Electricity Consumption from 2005 to 2018 individually.

From the multivariate regression analysis in Section 4.1.2, only GDP and Median Monthly Household Income have explanatory power of the Total Electricity Consumption in Singapore from 2005 to 2018. This result is in-line with the studies by Doshi et al. (2013), Chen (2017) and Li, Pizer and Wu (2018) where electricity consumption can be explained by GDP and household income. A mathematical model can be formulated based on the correlations of these 2 factors with Total Electricity Consumption for future electricity demand projection.

Based on single-variable and multivariate regression results, the Electricity Prices in Singapore do not correlate with Total Electricity consumption. This reason may be due to the fact that electricity prices were subjected to government regulation and oversight in Singapore in the 2000s and only started to be liberalised gradually from 2005. As seen in the Figure 4 below, the prices of electricity in Singapore from 2005 to 2019 are traded in a tight band between 20.0¢/kWh and 30.0¢ kWh.

Figure 4: Electricity Tariffs in Singapore from 2005 to 2019



Moreover the full liberalization of Singapore electricity market only occurred in 2018 with the launch of the Open Electricity Market which marks the final liberalization phase of Singapore electricity market. We would expect electricity consumption and electricity prices to be closely connected from 2019 onwards after the introduction of full competitions in the electricity market. Based on the above discussion, it is reasonable to see the lack of correlation between electricity prices and electricity consumption in our regressions from 2005 to 2018.

4.2 Research Question 2

<u>What is the statistical relationship between climate variables and the total electricity consumption in Singapore?</u>

Our second research question is to determine the relationship between climate factors and the total electricity consumption in Singapore. The climate factors are Average Daily Temperature, Average Relative Humidity, Annual Mean PSI PM2.5 Index, Annual Mean PSI PM10 index, Number of Rain Days per year and Mean Daily Sunshine hours. The data for these factors are detailed in Table 2 of Section 3.2.

4.2.1 Single-Variable Regression Models

Using the regression tool in Excel and Python, the individual climate factors were analysed against Singapore's Total Electricity Consumption from 2005 to 2018. The results of the various regression models are shown in Table 6 below.

Table 6: P-Values for Respective Independent Climate Variables (Single-Variable Regression Model)

Against Total Electricity Consumption						
	Average Daily Temp	Average Relative Humidity	PM 2.5	PM 10	Rain Days	Sunshine Hours
P-Values	0.27	0.007	0.096	0.61	0.98	0.32

Based on the criteria set for the P-values, key climate factors such as Average Daily Temperature, PM2.5 index, PM 10 index, Annual Number of Rain Days and Mean Daily Sunshine Hours are found not to have statistically significant correlation with Total Electricity Consumption in Singapore. This means these independent climate factors are not significant in explaining Total Electricity Consumption in Singapore (based on the data set from 2005 to 2018). Only Average Relative Humidity index exhibits a significant correlation with Total Electricity Consumption.

4.2.2 Multivariate Regression Model

Similar to the multivariate regression done for the socioeconomic factors in Section 4.1.2, the backward elimination regression method is employed to exclude the insignificant variables in the multivariate regression analysis. The climate factors that show statistical significance with Total Electricity Consumption are shown in Table 7.

Table 7: P-Values for Significant Climate Variables (Multivariate Variable Regression Model)

Against Total Electricity Consumption		
	Average Relative Humidity	PM 2.5
P-Values	0.004	0.041

Based on the regression, only Average Relative Humidity and PM2.5 have p-values of below 0.05 and are significant in determining the Total Electricity Consumption in Singapore based on the data set from 2005 to 2018.

4.2.3 Climate Variables and Residential Electricity Consumption

Residential Electricity Consumption comprised an average of 16% of Total Electricity Consumption in Singapore from 2005 to 2018. Given the importance of temperature increase in future climate change scenarios, we decided to conduct additional regression analysis on the residential household electricity consumption to investigate any potential relationships between residential household electricity consumption in Singapore and individual climate change factors.

Single-variable regressions were conducted for the climate factors against Residential Electricity Consumption from 2005 to 2018. The results for the various regression against residential/households electricity consumption are shown in Table 8 below.

Table 8: P-Values for Respective Independent Climate Variables (Single-Variable Regression Model)

Against Residential Electricity Consumption						
	Average Daily Temp	Average Humidity	PM 2.5	PM 10	Rain Days	Sunshine Hours
P-Values	**0.033**	**0.0004**	0.17	0.58	0.66	0.07

Against Residential Electricity Consumption, climate factors such as Average Daily Temperature and Average Relative Humidity Index are found to have statistically significant correlation with Residential Electricity Consumption in Singapore. This means these independent climate factors are significant in explaining the residential electricity consumption in Singapore (based on the data set from 2005 to 2018). Overall, the p-values of all the climate factors improved except for PM 2.5 index when regressing against Residential Electricity Consumption.

4.2.4 Discussions

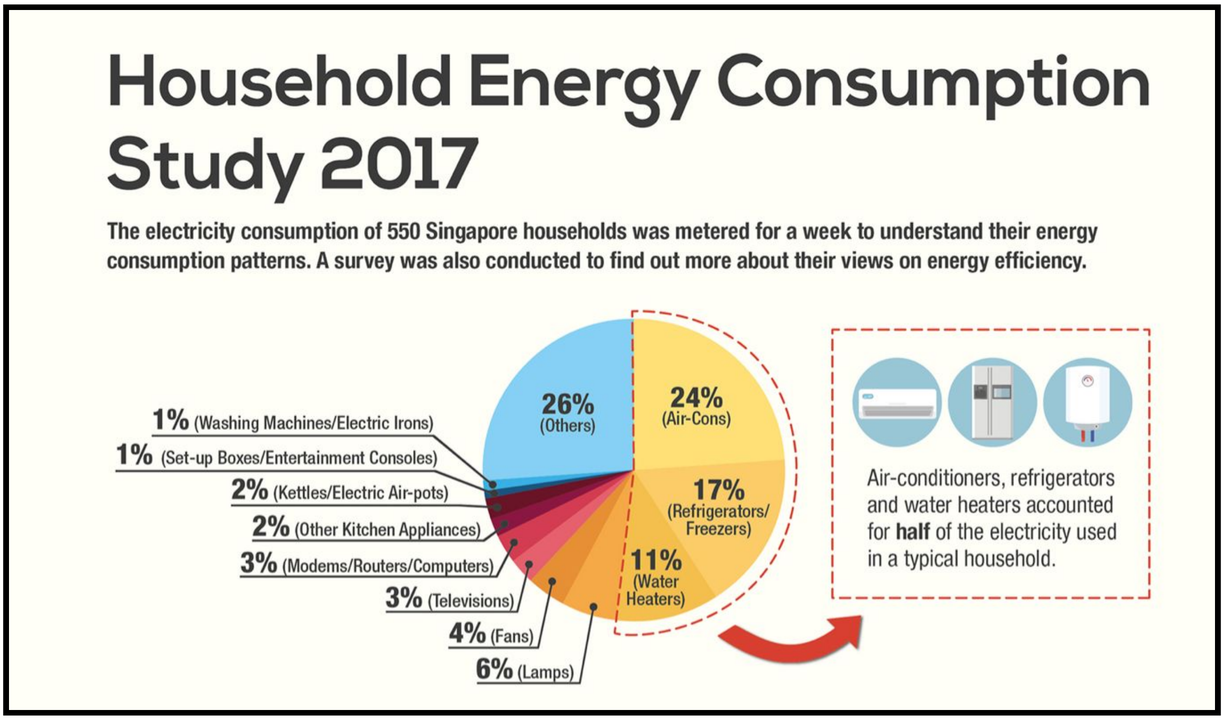
The single-variable and multivariate regression analysis done for climate factors with Total Electricity Consumption in Singapore for the data based on 2005 to 2018 shows that only climate factors such as Average Humidity and PM2.5 are correlated with the Total Consumption. Average Daily Temperature is not found to be a significant factor explaining in Total Electricity Consumption.

However, our results for single-variable regression modelling for Residential Electricity Consumptions showed that both Average Daily Temperature and Average Relative Humidity have significant individual correlation with Residential Electricity Consumption. <u>This relationship warrants a full multivariate regression analysis (with all the socioeconomic and climate factors) on the Residential Electricity Consumption in Section 4.3 so that we can understand Singapore's Residential Electricity Consumption as part of our study on Singapore's Total Electricity Consumption.</u>

The result above seems to suggest that residential households consumption are more likely to be affected by the change in daily temperature and relative humidity levels. For a typical residential household in Singapore, the household is unlikely to turn on air conditioners, dehumidifiers and fans throughout the day but only during times when the temperature and relative humidity have increased uncomfortably.

According to the National Environment Authority's Household Energy Consumption Study 2017 (see Figure 5 below), air conditioners took up 24% of all the household electricity consumption. Together with refrigerators, both air conditioning and refrigerators make up 51% of all household electricity consumption. These cooling equipment will increase the consumption of residential electricity as temperature and humidity rises. Therefore, residential household electricity consumption is more likely to be strongly correlated with temperature factors.

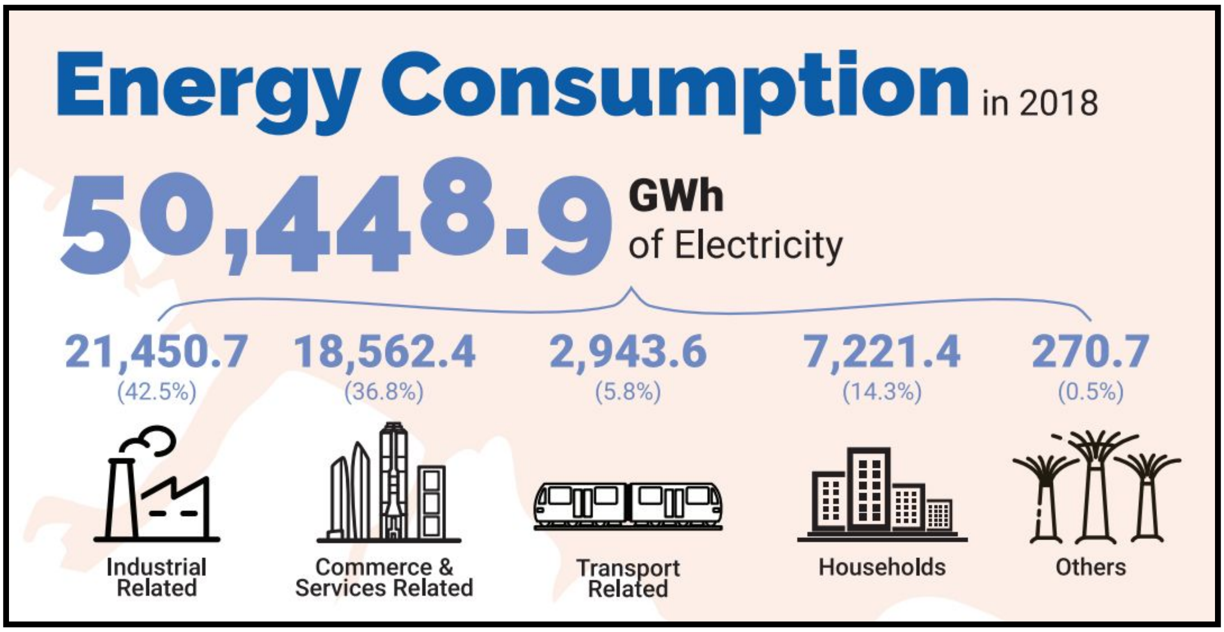
Figure 5. Singapore Home Energy Consumption Profile



Source: National Environment Authority

On the other hand, total electricity consumption in Singapore includes all industrial related, commercial & service related, and transport related electricity consumptions which contributed about 85% of all electricity consumption in Singapore in 2018 (see Figure 6 below). Regardless of the change in temperature and relative humidity of the day, these commercial and industrial entities in Singapore will continue to consume electricity given the economic activities. As a result, the impact of temperature and humidity changes are likely to be muted on the total electricity consumption.

Figure 6. Singapore Energy Consumption Profile



Source: Energy Market Authority

4.3 Research Question 3

<u>What is the multivariate relationship between climate change, socioeconomic variables and the electricity demand in Singapore?</u>

With the understanding from Research Question 1 and 2, we next determine the multivariate relationship between climate change, socioeconomic variables and the electricity demand in Singapore. In this analysis, **<u>all</u>** the socioeconomic and climate factors are collected against Singapore's Total Electricity Consumption. Given the analysis we did on Residential Electricity Consumption in Section 4.2.3, a separate multivariate regression model with all the socioeconomic and climate variables was generated for the residential electricity data as well.

4.3.1 Multivariate Regression Models

Using the backward elimination procedure, the final results of the multivariate regression modelling for all socioeconomic and climate factors against Total Electricity Consumption and Residential Electricity Consumption are shown in Table 9 below.

Table 9: P-Values for Significant Climate and Socioeconomic Variables (Multivariate Variable Regression Model)

Against Total Electricity Consumption		
	GDP	Median Monthly Household Income
P-Values	0.00028	0.027
Against Residential Electricity Consumption		
	Median Monthly Household Income	Average Daily Temp
P-Values	1.98×10^{-8}	2.2×10^{-4}

The detailed results are shown in Table 10 and 11.

Table 10: Final Results of Multivariate Regression (after Backward Elimination) Against Total Electricity Consumption

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.997180357
R Square	0.994368665
Adjusted R Square	0.993344786
Standard Error	403.8700488
Observations	14

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	316819596.6	158409798.3	971.1778019	4.24974E-13
Residual	11	1794221.18	163111.0163		
Total	13	318613817.8			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	22682.73842	635.5930763	35.68751653	1.00555E-12	21283.80749	24081.66935	21283.80749	24081.669
GDP	0.037182003	0.00710983	5.229661214	0.000281276	0.021533373	0.052830634	0.021533373	0.0528306
HH Income	1.037208592	0.407725188	2.543891384	0.02729028	0.139811504	1.934605679	0.139811504	1.9346057

Table 11: Final Results of Multivariate Regression (after Backward Elimination) Against Residential Electricity Consumption

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.982426928
R Square	0.965162669
Adjusted R Square	0.958828609
Standard Error	101.3394683
Observations	14

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	3129720.646	1564860.323	152.3766202	9.57738E-09
Residual	11	112966.5662	10269.68784		
Total	13	3242687.212			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-10635.25876	2831.202661	-3.756445592	0.003174191	-16866.6938	-4403.823715	-16866.6938	-4403.8237
Daily Average Temp	553.3768515	103.0540358	5.369773706	0.000226862	326.5564481	780.1972549	326.5564481	780.19725
HH Income	0.268301165	0.018853985	14.2304749	1.98141E-08	0.226803823	0.309798507	0.226803823	0.3097985

For Total Electricity Consumption regression (Table 10), only GDP and Median Monthly Household Income have a strong correlation with the Total Electricity Consumption data set from 2005 to 2018, i.e. p-values are less than 0.05 each. The analysis shows that socioeconomic factors are better in explaining the total electricity consumption in Singapore. This is consistent with the correlation results in Section 4.1 and Section 4.2 where Total Electricity Consumption is strongly correlated with socioeconomic factors and not climate factors.

In addition to the individual p-values of the GDP and Median Monthly Household Income in Table 10, the F-test of significance of the regression (4.2×10^{-13}) is also well below the significance level of 0.05. The F-test of significance indicates whether the regression model provides a better fit to the data than a model that contains no independent variables. In addition, the R-squared of the multivariate analysis in Table is at a very high level of 0.99 (or 99%). R-squared is a statistical measure of how close the data are to the fitted regression model, In general the higher the R-squared, the better fit the regression model fits the data.

For Residential Electricity Consumption (as shown in Table 9 and 11), both Median Monthly Household Income and Average Temperature exhibit statistical significant relationships with the Residential Electricity Consumption data set.

The F-test of significance and R-squared values for the Residential Electricity Consumption regression model are also at very high significance levels of 9.5×10^{-9}

and 0.965 respectively. These indicate the Residential Electricity Consumption model in Table 11 also fits the data very well.

The results for the regression for Residential Electricity Consumption reinforce the reasonable conclusion that residential households electricity consumption are more likely to be affected by the change in daily temperature and climate change scenarios in future Singapore than commercial/industrial entities.

4.3.2 Discussions

Following the analysis in Section 4.3.1, a mathematical model for forecasting Total Electricity consumption can be formulated using GDP and Median Monthly Household Income as independent factors as climate factors do not have any strong correlation with total electricity consumption. Given that GDP measures the total economic activities of Singapore and Total Electricity Consumption includes all commercial and industrial usage, it is not surprising that GDP is a significant factor in explaining Total Electricity Consumption.

As for Residential Electricity Consumption, Average Temp and Median Monthly Household Income are statistically significant in the multivariate regression and a mathematical model for forecasting Residential Electricity Consumption can be formulated using both factors as independent variables.

It is important to note that in addition to Average Temp, Median Monthly Household Income is also a significant factor impacting on Residential Electricity Consumption. As average household income rises, the households are likely to purchase more electrical appliances or white consumer goods which will contribute to higher residential electricity consumption. As mentioned in Chen (2017), the development in socioeconomic status of households through increasing income causes rises in living standards, and eventually stimulates an increase in electricity consumption, especially if alternative energy at home is not available.

Given the impact of temperature on Residential Electricity Consumption (analysis in Section 4.2.4) and the impact of rising income on electricity consumption , any mitigation strategies for the climate change scenario for Singapore should also focus on the efficient use of electricity in the residential sector. Such strategies for policy-makers may include incentivising the use of more energy efficient electrical appliances (e.g. through rebates), enforcing green labelling schemes and electricity efficiency standards, and innovative redesign of household appliances.

4.4 Research Question 4

<u>What is the projected consumption for electricity in Singapore in 2050 based on the RCP 4.5 and RCP 8.5 climate scenarios?</u>

4.4.1 Forecast for GDP and Media Monthly Household Income in 2050

The GDP projection for Singapore to 2050 is based on the assumption that GDP growth in Singapore over the period to 2050 will be at 2% per annual. According to DBS Bank, taking into consideration productivity and demographics trends and structural reforms, a baseline of 2 to 2.5 % GDP growth on average over the period to 2030 is a good starting point. The project will assume the same growth rate of 2% will apply from 2030 to 2050 as well.

To account for the impact of COVID-19 on Singapore's economy this year, the GDP forecast for 2020 is assumed to be -5% based on the latest estimates from the Ministry of Trade and Industry provided on the 11 August 2020.

The GDP projections for Singapore from 2020 to 2050 is shown in Table 12 below.

Table 12 GDP Projection for Singapore from 2020 to 2050

GDP ($m)			
Yr 2020	Yr 2030	Yr 2040	Yr 2050
$492,341	$587,786	$716,508	$873,419

For the Median Monthly Household Income projection, a compound annual growth rate (CAGR) of 4% is used to project the Median Monthly Income in 2020 to 2050 (as shown in Table 13). The CAGR is based on the historical growth rate of Singapore's Median Monthly Household Income from 2000 to 2019 of 4.1%.

Table 13 Median Monthly Household Income Projection for Singapore from 2020 to 2050

Median Monthly Household Income (S$)		
Yr 2020	Yr 2030	Yr 2050
\$9,425	\$14,077	\$31,402

4.4.2 Forecast for Average Temperature based on RCP 4.5 and RCP 8.5

According to Dr Muhammad Eeqmal Hassim, Senior Research Scientist, Centre for Climate Research Singapore, over the last 60 years, Singapore's average temperature has increased by 0.25 degree per decade versus a global temperature increase of 0.12 degree per decade. This is due to the high urbanization rate in Singapore. Without considering the impact of climate change in Singapore, the Base Case for temperature increase for Singapore should be based on 0.25 degree increase per decade.

Table 14 below provides the estimated temperature projection for Singapore for the period 2040-2069 and 2070-2099 based on the RCP 4.5 and RCP 8.5 scenarios. Given that the normal practice is to calculate the mean temperature change over 30 year periods to smooth out the interannual variations, we calculated the mid point of the high and low Mean Temp (for the period 2040 to 2069 for RCP 4.5 and RCP 8.5) and used it as a proxy for our 2050 temperature. For further analysis, we also used the high Mean Temp (29.6 degree for RCP 4.5 and 30.3 degree for RCP 8.5) in our 2050 projection to evaluate the potential consequences of a higher temperature in 2050.

Table 14 Temperature Projection for Singapore in 2050 based on RCP 4.5 and RCP 8.5 (*Source*: *Centre for Climate Research Singapore)*

		Mid-century (2040 - 2069)				End-century (2070 - 2099)			
Mean observed (1980 - 2009)		RCP4.5		RCP8.5		RCP4.5		RCP8.5	
Minimum Temp (deg C)	24.1	25.4	26.4	25.9	27.1	25.5	27.0	27.0	28.9
Mean Temp (deg C)	27.4	28.7	29.6	29.2	30.3	28.8	30.1	30.3	32.0
Maximum Temp (deg C)	31.8	33.1	34.5	33.8	34.9	33.3	34.6	34.9	36.7

Table 15 below provides a summary of the temperature ranges based on the Base Case, RCP 4.5 and RCP 8.5.

Table 15 Average Daily Temperature Projection for Singapore in 2050

Scenario	2010	2020	2030	2040	2050 (estimated)
Base Case	27.7	27.9	28.20	28.45	28.70
RCP 4.5 (Mid)					29.15
RCP 4.5 (High)					29.60
RCP 8.5 (Mid)					29.75
RCP 8.5 (High)					30.30

The RCP 8.5 (High) scenario's temperature is projected to be 30.30 degrees in 2050 which can be considered as a worst case scenario for Singapore's temperature in 2050.

4.4.3 Electricity Consumption Projection and Discussion

Based on the regression results in Section 4.3, the following mathematical model can be determined for Total Electricity Consumption in Singapore:

<u>Total Electricity Consumption Model:</u>

$$E_t = 22682 + 0.037\ GDP_t + 1.037\ HI_t$$

where E is the Total Electricity Consumption in Singapore;

GDP is the Gross Domestic Product of Singapore; and

HI is the Median Monthly Household Income

The following mathematical model can be determined for Residential Electricity Consumption in Singapore:

<u>Residential Electricity Consumption Model:</u>

$$\mathbf{E_R = -10635 + 0.2683\ HI_t + 553.37\ T_t}$$

where E_R *is the Residential electricity consumption in Singapore;*

HI_t *is the Median Monthly Household income; and*

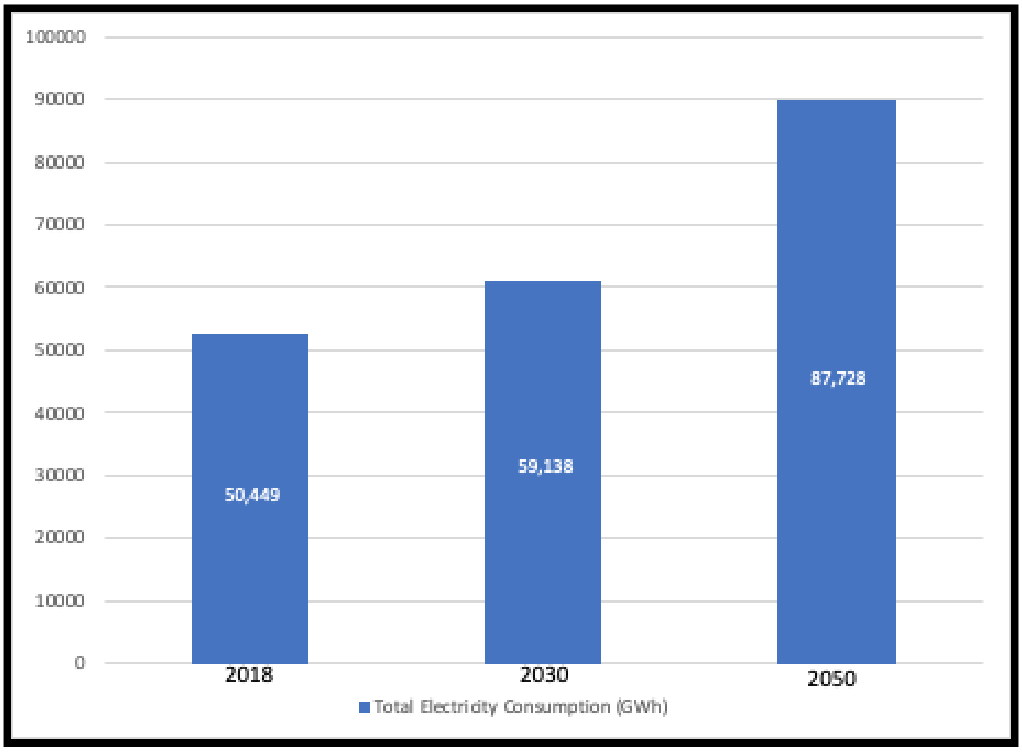
T_t *is the Annual Average Daily Temperature,*

The results of the various projections are shown in the tables below. Table 16 and Figure 7 presents the estimated Total Electricity Consumption in Singapore from 2018 to 2050.

Table 16 Total Electricity Consumption in 2030 and 2050

Year	Total Electricity Consumption (GWh)
2018	50,449
2030	59,138
2050	87,728

Figure 7: Estimated Total Electricity Consumption (GWh)



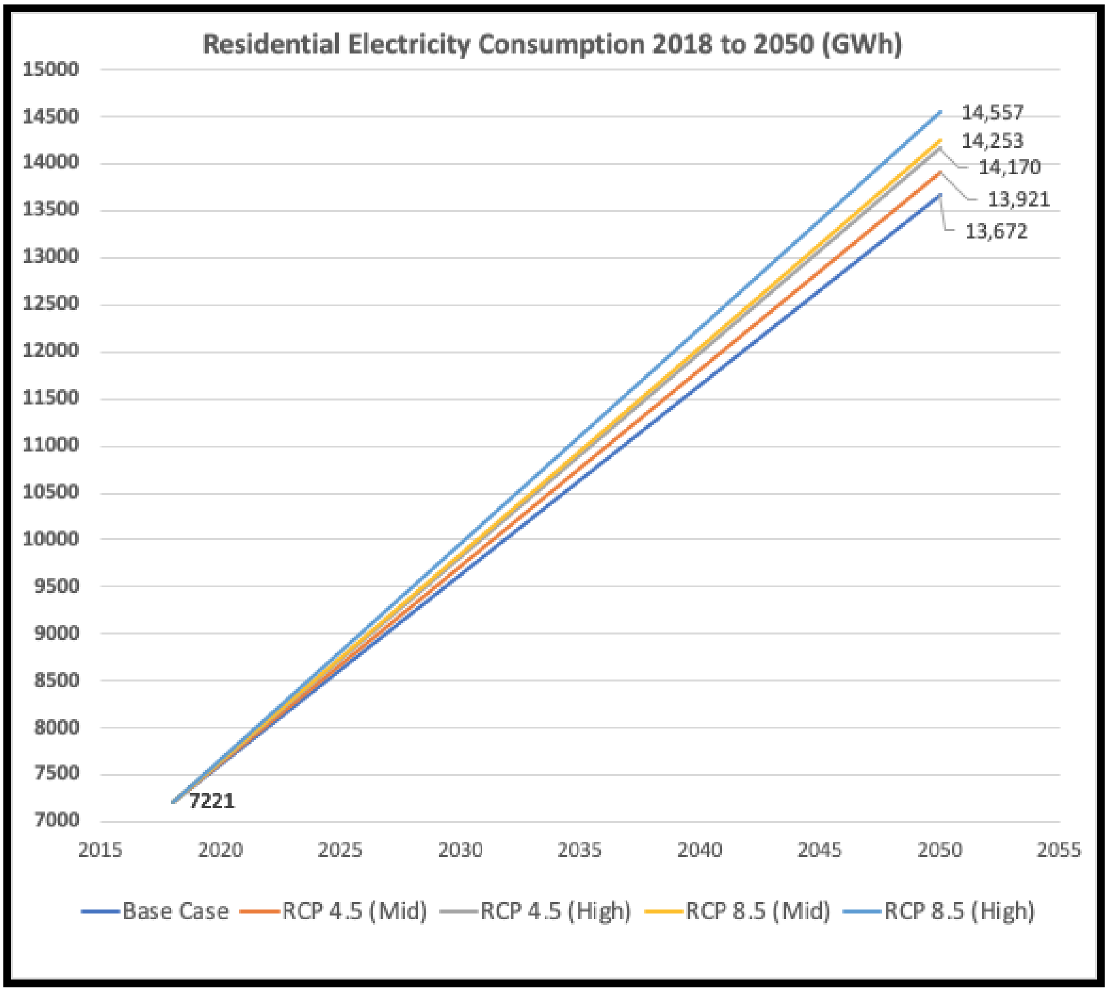
Total Electricity Consumption is expected to grow from 50,499 GWh in 2018 to 87,728 GWh in 2050, representing a 73.9% increase in consumption. Based on the historical Total Consumption data from 2000 to 2018, the increase in total electricity consumption during this 18-year period was close to 72% in Singapore. Therefore, given the expected slowdown in GDP growth and median household income growth in the next 30 years, it is not unreasonable to see only a 73.9% increase in total electricity consumption from 2018 to 2050.

Table 17 and Figure 8 presents the estimated Residential Electricity Consumption in Singapore from 2018 to 2050.

Table 17 Estimated Residential Electricity Consumption in 2050

Scenarios	Year	Residential Electricity Consumption (GWh)	Increase from Base Case	Increase from 2018 Levels
Historical	2018	7,221	NA	NA
Base Case	2050	13,672	NA	89.3%
RCP 4.5 (Mid)	2050	13,921	1.8%	92.8%
RCP 4.5 (High)	2050	14,170	3.6%	96.2%
RCP 8.5 (Mid)	2050	14,253	4.2%	97.4%
RCP 8.5 (High)	2050	14,557	6.5%	101.6%

Figure 8: Estimated Residential Electricity Consumption (GWh) based on Climate Change Scenarios



Our Base Case scenario (without consideration of any climate changes scenarios) projected that Residential Electricity Consumption will increase from 7,221 GWh in 2018 to 13,672 GWh in 2050. Due to the high urbanization rate in Singapore, under the Base Case scenario, residential electricity consumption is projected to increase by a huge 89.3% from 2018 levels.

When climate change with temperature increase under the RCP 4.5 Mid and RCP 4.5 High scenario are considered, our analysis shows that the increase in temperature under both scenarios have an estimated 1.8% to 3.6% impact on the Base Case consumption. Under the RCP 4.5 Mid Scenario, Residential Electricity Consumption will increase to 13,921 GWh in 2050 and 14,170 GWh under the RCP 8.5 scenario.

Under the RCP 8.5 Mid and RCP 8.5 High scenario, the increase in temperature has an estimated 4.2% to 6.5% impact on the Base Case Residential Electricity Consumption.

Depending on the severity of climate change scenarios, residential electricity consumption will likely see a significant increase of between 92.8% to 101.6% in consumption compared with the 2018 consumption levels.

5) Conclusions

In this paper, we have investigated how electricity consumption is statistically related to Singapore's socioeconomic and climate variables through the use of single-variable and multivariate regression with backward elimination procedure. With the results from the regression analysis, we have also predicted the impact of climate changes on electricity consumption and prices in Singapore in 2050 based on the RCP 4.5 and RCP 8.5 climate change scenarios. Our analysis has shown that Total Electricity Consumption only correlates with GDP and Median Monthly Household Income in the multivariate regression and Electricity Price is not correlated with Total Electricity Consumption in all regressions. Total Electricity Consumption in 2050 is projected to be 73.9% above 2018 levels based on our mathematical model with GDP and Median Monthly Income.

Our research has also revealed that Singapore's Residential Electricity Consumption has significant correlation with both Average Monthly Household Income and Average Daily Temperature and hence climate change is likely to have a greater impact on Singapore's residential households than commercial/industrial entities. The projected increase in temperatures in 2050 due to RCP 4.5 and RCP 8.5 are estimated to have a 1.8% to 6.5% impact on Singapore's residential electricity consumption in 2050 (compared to the Base Case residential electricity consumption) and residential electricity consumption in 2050 is expected to be 101.6% above 2018 levels in the worst case scenario (RCP 8.5 High).

The significant increase in Residential Electricity Consumption by 2050 based on the RCP 4.5 and RCP 8.5 scenarios points to the importance of implementing mitigation strategies such as electricity efficiency schemes and innovative energy-efficient appliances to lessen the impact on a typical Singapore household.

5.1) Limitations and Extensions

The regression results and implications of this study coincides with other studies on climate change and electricity consumption. However, there are several limitations and possible extensions that should be considered for future research on the subject.

Firstly our analysis is based on annual numbers which limit the number of data points available in our regression (14 observation points). More data points are preferred in any regression studies to ensure a more representative outcome. One way to overcome the limited number of data points is to utilize monthly data points or even daily data points instead of annual data points. In addition to more data points for analysis, one possible benefit of using monthly data is that seasonal patterns for electricity consumption can be studied as well.

Secondly, given the non-exact science nature in climate change studies, it is very difficult to predict a specific temperature in a specific location for a specific year. In this study, we have to estimate the possible temperature in 2050 using the RCP 4.5 and RCP 8.5 scenarios' which are based on a 30-years period forecast. As such, it may be better for future study to look at utilising a range of temperatures for a particular year rather than a point forecast for that year. Additionally, future studies can focus on predicting the electricity consumption closer to the current year 2020 (e.g. forecasting 2030 instead of forecasting 2050) to reduce the forecast error over a longer period of time.

Thirdly, we have utilized the results of our multivariate regressions to create the mathematical models for future electricity consumptions. The study's forecast approach is rather simplistic and more robust forecast methods with advanced statistical methods can be employed for more comprehensive and robust electricity consumption projections. Moreover, the mathematical models we have formulated in this study assume the relationships between the dependent variable and independent variables remain consistent throughout the next few decades to establish a forecast in 2050. It may be more suitable to forecast closer to the current year than trying to forecast decades ahead as we have mentioned in the previous paragraph.

Fourthly, climate change impact on industrial/commercial electricity consumption is not definitive in our regressions. Further investigation with monthly data of commercial/industrial electricity consumption can be helpful in understanding how temperature change will impact on commercial and industrial electricity consumption in Singapore.

Fifthly, as our study has not shown the correlation between total electricity consumption and electricity prices, further analysis is required to understand the relationships between climate and socioeconomic variables with electricity prices.

With the full liberalisation in 2018, the latest price data from Singapore electricity market will be useful in evaluating the statistical relationship between electricity consumption and prices.

Lastly, given the projected impact of climate change and income on residential electricity consumption, the relationship between residential electrical appliances usage and electricity consumption in Singapore can be explored for better mitigation strategies in the future.

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Appendix

Terminology

Term	Definition
Global warming	Global warming is the long-term rise in the average temperature of the Earth's climate system. It is a major aspect of climate change and has been demonstrated by direct temperature measurements together with measurements of various effects of the warming. Global warming and climate change are often used interchangeably. Global warming will cause a sudden increase or decrease in rainfall, the rise in mean sea level, glacial ablation, etc. The average global temperature between 1981 and 1990 was 0.48℃ higher than 100 years earlier.
Electricity consumption or demand	Electricity consumption or demand is measured in gigawatt-hours (GWh) and represents the amount of electricity that has been consumed over a certain time period.
Mathematical Modelling	Mathematical Model is used to describe a system using mathematical concepts and languages. It can help

	scientists explain a system, study the impact of different components and make a prediction of the trend.
Multivariate Regression Analysis	Regression analysis is a set of statistical processes for estimating the relationships between a dependent variable (often called the 'outcome variable') and one or more independent variables (often called 'predictors', 'covariates', or 'features'). **Multivariate analysis** deals with the statistical **analysis** of data collected from more than one dependent variable. These variables may be correlated with each other, and their statistical dependence is often taken into account when analyzing such data.
Data science	Data Science is a form of science where one extracts the valuable part of data from the existing data and analyses to get the result related to the data. It includes applied mathematics, statistics, pattern recognition, pattern recognition, data visualization, data warehouse (DW) and high-performance computing.
RCP 4.5 and 8.5	RCPs are prescribed pathways for greenhouse gas and aerosol concentrations, together with land use change. They are consistent with a set of broad climate outcomes

	utilised by the climate modelling community. The pathways are characterised by the radiative forcing which was produced by the end of the 21st century. Radiative forcing refers to the extra heat the lower atmosphere will retain as a result of additional greenhouse gases, measured in Watts per square metre (W/m^2). RCP 8.5 envisions a future with little curbing of emissions, with a CO_2 concentration continuing to rise rapidly, reaching 940 ppm by 2100. RCP 4.5 - CO_2 concentrations are slightly above those of RCP 6.0 until after mid-century, but emissions peak earlier (around 2040), and the CO_2 concentration reaches 540 ppm by 2100.