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Title
Projections of Future Electricity Consumption in Tokyo and New York under the Influence of Global Warming

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Author
Otaki, Takuma

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Takuma Otaki

Projections of future electricity consumption in Tokyo and New York under the influence of global warming

1. Motivation

There is a close relationship between climate change and energy consumption. Climate change causes not only temperatures to rise, but also impacts atmospheric circulation and exerts specific regional impacts. Can the world's largest metropolitan areas adapt to future climate change from a perspective of energy consumption for electricity consumption? Thus, I will explore the relationship between electricity consumption and weather conditions.

Reducing energy consumption is important for mitigating climate change. In order to provide robust policy recommendations for future energy demand, it will be necessary to capture characteristics of energy consumption in big metropolitans of this world: New York City (NYC) and Tokyo. NYC and Tokyo are classified in same climate zones by humid subtropical (Koppen cfa), and both cities have four seasons. Factors which change trends of electricity consumption can be extracted by observing cities under similar climate condition. Of course, there are various ways for consuming energy like lighting, cooling or heating something, transporting people and freights, and there are various energy sources for covering the energy demand. This paper especially focuses on electricity consumption in metropolitans because many energy sources of functions in our life seem to be consolidated in electricity like household electric appliances (rice cookers, air conditioners, kitchen stoves etc.) and transportation (from only car to electric railcar and electric car). Thus, managing the demand of electricity would be more important problem for mitigating climate change. By comparing these metropolitans, this paper tries to extract best (and worst) practices, leading to potential paths for mitigating climate change by reducing electricity consumption.

2. Quantitative analysis on relationships between electricity consumption and weather condition

For thinking appropriate ways to manage electricity consumption from a perspective of climate change is confirming the relationship between electricity consumption and weather conditions. Specifically, what is the relationship between electricity consumption and temperature? We intuitively know that we consume electricity for cooling and heating. This section tries to make it clearer the relationship between weather and electricity consumption based on quantitative data. This section starts from interpreting observed data of electricity consumption and weather condition, and makes a model for explaining the relationship.

1) Interpretation of observed data (kW/capita versus air temperature (ºC))

Figure 1 is plot figures which show observed data of electricity consumption per capita (kW/capita) and air temperature in NYC and Tokyo in 2017. These figures show three clear facts that: i) NYC gets higher value of kW/capita in summer season although average temperature is lower than Tokyo, ii) NYC gets lower value of kW/capita than Tokyo in winter season although average temperature is lower than Tokyo and iii) even under similar temperature, values of kW/capita seem to fluctuate.

Considering these facts, three hypotheses could be made that: i) extreme temperature (both warm and cold) have impact on values of kW/capita at least in Tokyo, ii) there are other daily or weekly cycles which influence on kW/capita because there are observed samples which show systematic change under similar temperature and iii) energy sources for heating buildings is different between NYC and Tokyo.

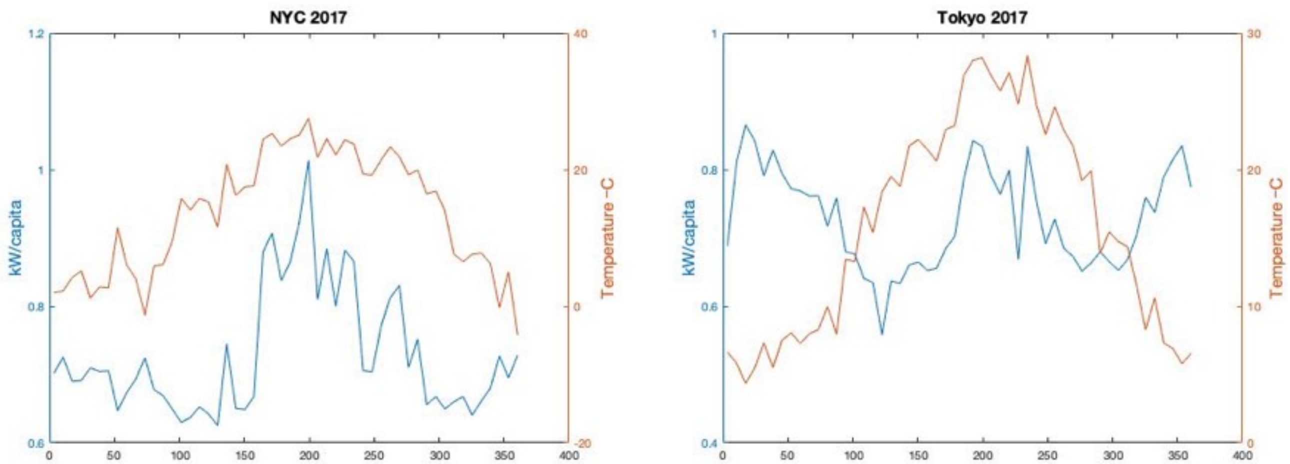

Figure 1: Plots of daily data of kW per capita (blue lines) and daily average temperature (red lines) in time scale (365 days) in both NYC and Tokyo

2) Modeling the relationship between kW/capita and air temperature

For statistically verifying the hypotheses i) extreme temperature (both warm and cold) have impact on values of kW/capita at least in Tokyo and ii) there are other daily or weekly cycles which influence on kW/capita made in last section, this section tries to make models which explains the relationship between kW/capita and air temperature. Considering the observation in section 2.1), temperature should be incorporate in the models. And, reflecting daily or weekly cycles in the model, sine and cosine also should be included in the models. And for fitting the model to wave shaped observed data, value of cubic of air temperature and value of square of air temperature can be candidates of crucial independent variables of the models. Considering these factors, the models should be that:

$$kW\ per\ capita = \beta_0 + \beta_1\, T^3 + \beta_2\, T^2 + \beta_3\, T + \beta_4 \cos\left(2\pi \times \frac{t}{365.25}\right) + \beta_5 \sin\left(2\pi \times \frac{t}{365.25}\right).$$

And, Table 1 shows the results of non-linear regression of models for explaining consumption of electricity per capita (kW/capita) in both NYC and Tokyo. As the table shows, coefficients of all variables are statistically significant and the results show both of these models explain the value of kW/capita in each metropolitan pretty well.

	Intercept	T^3	T^2	T	Cos	Sin
kW/capita of NYC	0.7147	0.0000	-0.0005	-0.0065	0.0103	-0.0029
P<0.05	(0.6954~ 0.7341)	(0.0000~ 0.0001)	(-0.0008~ -0.0002)	(-0.0093~ -0.0037)	(-0.0069~ 0.0275)	(-0.0008~ -0.0002)
R^2 = 0.9777, F-static = 404.2371, P-value = 0.0000, Estimation of the error variance = 0.0002						
kW/capita of Tokyo	0.9810	0.0000	-0.0003	-0.0254	-0.0134	-0.0141
P<0.05	(0.8743~ 1.0878)	(0.0000~ 0.0001)	(-0.0016~ 0.0010)	(-0.0448~ -0.0059)	(-0.0633~ 0.0365)	(-0.0366~ -0.0084)

R^2 = 0.8999, F-static = 82.6858.2371, P-value = 0.0000, Estimation of the error variance = 0.0006

Table 1: Coefficient rates and stats summaries of models for NYC and Tokyo

Figure 2 shows how the models explain real observed values pretty well. Especially, the model for NYC succeeds to explain observed data almost perfectly through all seasons. On the other hand, the model for Tokyo fail to explain a few parts of observed data, and there are three big gaps between observed data and modeled data in around day 1 (1st week of January), day 120 (1st week of May), and day 225 (2nd weekend of August). But, these outliers can be explained by Japanese cultural behaviors. People in Tokyo tend to go back their home town in new year holidays (1st week of January) and Obon holidays (2nd weekend of August) for visiting ancestor's graves. And, there are serial national holidays in 1st week of May, so Japanese people tend to travel in that period. Thus, many people leave Tokyo in these periods, so, electricity demand decrease and get far from the values which are predicted by the model. Except for these special periods, the model for Tokyo also explain observed data well.

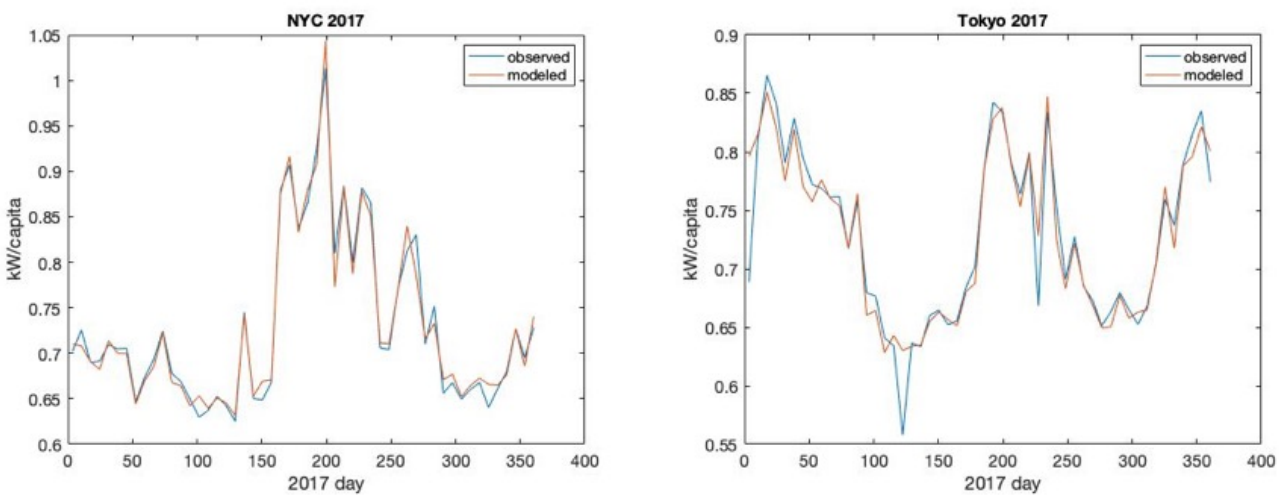

Figure 2: Plots of observed kW/capita in daily time scale (blue lines) and modeled kW/capita in daily time scale (red lines)

Figure 3 clearly show the relationship between kW/capita and air temperature. And, three characteristics can be observed from the figure that: i) values of kW/capita are similar in both cities in moderate situation (around 15ºC), ii) values of kW/capita in NYC is higher than in Tokyo in warmer situation (above 20ºC) and iii) values of kW/capita in Tokyo is higher than in NYC in colder situation (below 15ºC). And figure 3 and the models verify the hypotheses that i) extreme temperature (both warm and cold) have impact on values of kW/capita at least in not only Tokyo but also in NYC.

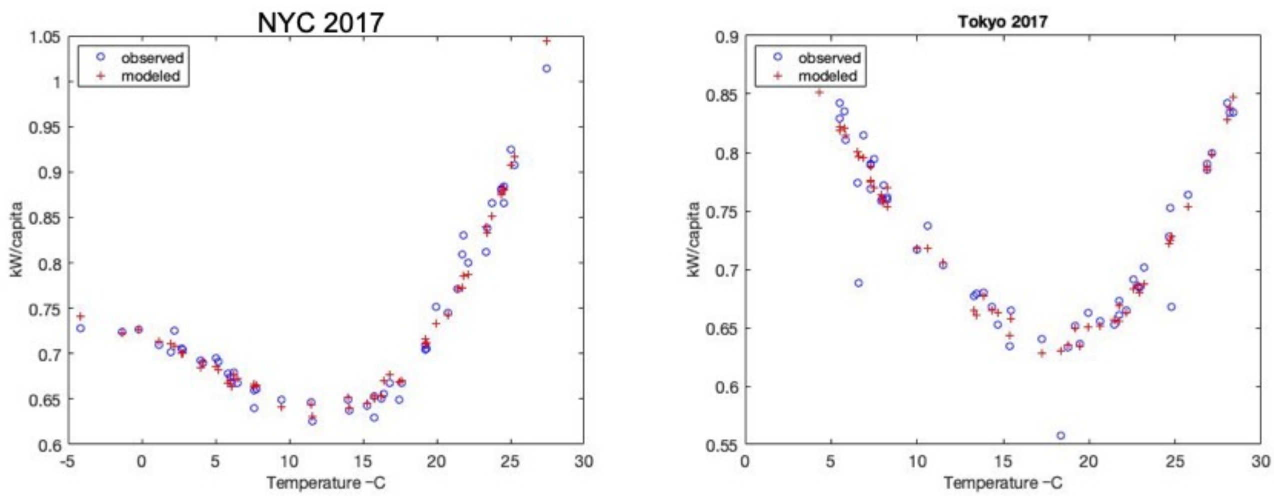

Figure 3: Plots of observed kW/capita in daily time scale and modeled kW/capita in daily time scale

And, there are survey results which verify the hypothesis iii) energy sources for heating buildings is different between NYC and Tokyo. There are survey results which shows that 69% of people in Tokyo choose electricity as an energy source for heating their buildings although only 9% of people in NYC choose electricity as an energy source for heating their buildings (Table 2 and Table 3). There are three controversial points about these data that: i) data of Tokyo is slightly old, ii) data of Tokyo was surveyed by electricity company although the data of New York was surveyed by a part of government (data of Tokyo might be biased) and iii) both data of New York and Tokyo include the data from suburb area, but suburb areas of New York is larger than the suburb areas of Tokyo (if there is data which only reflects NYC, the result might be different). However, these results are enough convincing for confirming the trend that people in Tokyo choose electricity as an energy source for heating their buildings comparing with people in NYC.

HOUSE HEATING FUEL of New York (Unit: Occupied housing (OH))				
Year	2017		2010	
	OH	%	OH	%
Total	7304332		7196427	
Utility gas	4339349	59%	3961085	55%
Bottled, tank, or LP gas	294973	4%	227607	3%
Electricity	**867925**	**12%**	**676262**	**9%**
Fuel oil, kerosene, etc	1496843	20%	2068004	29%
Coal or coke	17881	0%	19949	0%
Wood	122088	2%	143242	2%
Solar energy	5988	0%	1823	0%
Other fuel	77386	1%	61664	1%
No fuel used	81899	1%	36791	1%

Table 2: House heating fuel of New York (Made by author from the source: U.S. Census Bureau, 2017)

HOUSE HEATING FUEL of Tokyo (Unit: Occupied housing (OH)) in 2010			
		OH	%
Total		**1956**	
Electricity		**1350**	**69%**
	Air conditioner	645	33%
	Kotatsu	215	11%
	Floor heating system	176	9%
	Electric heating carpets	157	8%
	Electric heating stove	157	8%
Fuel oil, kerosene, etc		**391**	**20%**
	Stove & Fan heater	391	20%
Gas		**215**	**11%**
	Stove & Fan heater	215	11%

Table 3: House heating fuel of Tokyo (Made by author from the source: TEPCO, 2010)

3) Modeling for verifying time cycles

This section focuses on more deeply on verifying time cycles. Based on same processes to section 2.2), this section starts from confirming the trends of electricity consumption and making models for verifying day-night cycles for both cities, this means that total four models are made in this section. The main reason for verifying day-time and night time cycle is that climate change should has different effects on daytime and night time and especially air temperature change would be different, thus, separated models are needed for predicting future effects of climate change on electricity consumption.

Figure 4 shows observed data of weekly averaged temperature in both cities, and figure 5 shows weekly averaged kW/capita of daytime (from 06:00 to 18:00) and nighttime (from 18:00 to 06:00) in both cities. These figures show that kW/capita is lower in nighttime than kW/capita in daytime as expected, both gaps of kW/capita and temperature between daytime and nighttime are larger in Tokyo than the gaps in NYC, and waveforms of kW/capita in Tokyo between daytime and nighttime are a little bit different although waveforms of NYC are similar. These things might implicate many things, but this section focuses on confirming gaps of elasticity of kW/capita and air temperature by modeling, so confirming the fact that there are certain gaps between daytime and nighttime is enough.

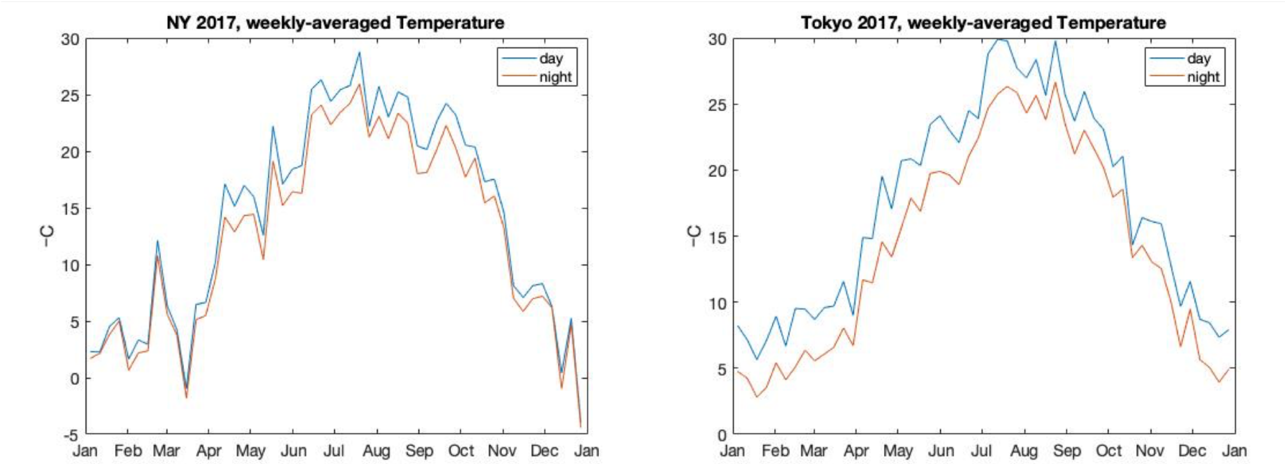

Figure 4: Weekly averaged temperature of daytime (blue lines) and nighttime (red lines) in both cities

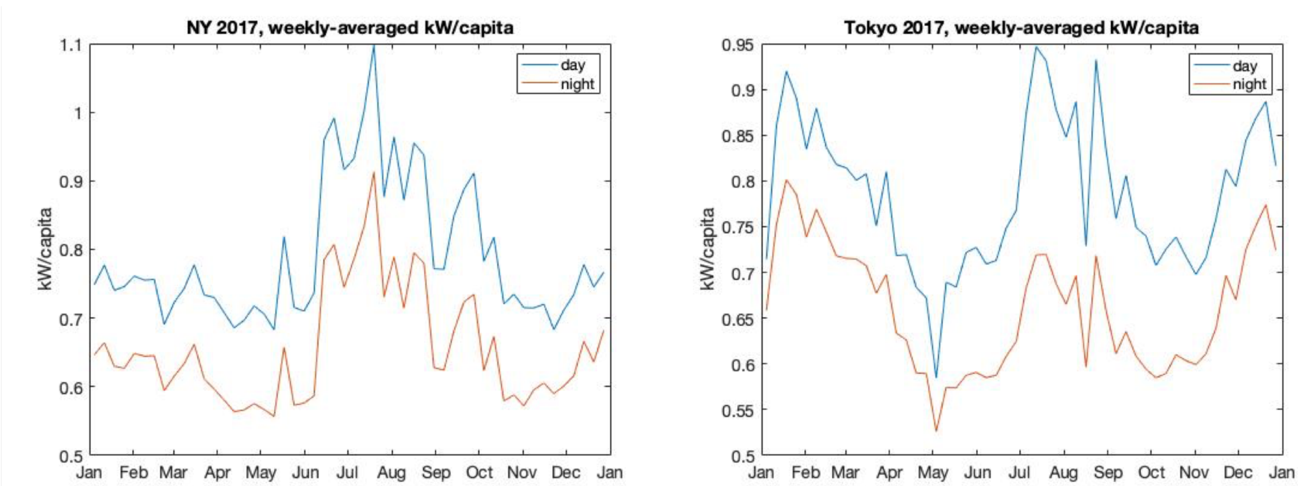

Figure 5: Weekly averaged kW/capita of daytime (blue lines) and nighttime (red lines) in both cities

As Figure 4 and Figure 5 show, there are certain gaps of kW/capita between daytime and nighttime, so making models separately for both daytime and nighttime is fair. From the results of 2.2), the model which includes temperature and time worked pretty well for explaining the relationship between kW/capita and air temperature. Thus, this section also starts from applying same model to both daytime and nighttime.

$$kW\ per\ capita = \beta_0 + \beta_1\, T^3 + \beta_2\, T^2 + \beta_3\, T + \beta_4 \cos\left(2\pi \times \frac{t}{365.25}\right) + \beta_5 \sin\left(2\pi \times \frac{t}{365.25}\right).$$

As Table 4 and Table 5 show, all of coefficients are statistically significant, and R^2 of models are pretty high. And, Figure 6 shows that observed kW/capita of daytime and nighttime in scale of temperature are very well explained by the models.

Of course, not only air temperature, but also other weather factors, like wind speed, the amount precipitation and relative humidity are tested whether these factors would be crucial factors for explaining electricity consumption. However, there were not certain effects on electricity consumption from these factors at least from observing only single year. There should be potential for explaining certain relationships between electricity consumption and weather conditions if other years are considered as panel data set. But, as first step of processes for making relationships between electricity consumption and weather conditions clearer and forecasting values of kW/capita in future, these results acquired related with relationship between air temperature and electricity consumption acquired by cross-section analysis fairly enough usable.

	Intercept	T^3	T^2	T	Cos	Sin
Daytime kW/capita of NYC	0.7740	0.0000	-0.0005	-0.0056	-0.0005	-0.0072
P<0.05	(0.6954~ 0.7341)	(0.0000~ 0.0000)	(-0.0009~ -0.0002)	(-0.0091~ -0.0020)	(-0.0230~ 0.0220)	(-0.0153~ -0.0010)
R^2 = 0.9719, F-static = 317.7849, P-value = 0.0000, Estimation of the error variance = 0.0003						
Nighttime kW/capita of NYC	0.7587	0.0000	-0.0005	-0.0061	0.0112	-0.0040
P<0.05	(0.8743~ 1.0878)	(0.0000~ 0.0001)	(-0.0008~ -0.0001)	(-0.0093~ -0.0030)	(-0.0107~ 0.0330)	(-0.0121~ 0.0042)
R^2 = 0.9736, F-static = 339.6237.2371, P-value = 0.0000, Estimation of the error variance = 0.0003						

Table 4: Coefficient rates and stats summaries of models for NYC (daytime and nighttime)

	Intercept	T^3	T^2	T	Cos	Sin
Daytime kW/capita of Tokyo	1.1087	0.0000	-0.0004	-0.0286	0.0330	-0.0193
P<0.05	(0.9550~ 1.2624)	(0.0000~ 0.0001)	(-0.0020~ -0.0013)	(-0.0559~ -0.0013)	(-0.0913~ 0.0252)	(-0.0335~ -0.0050)
R^2 = 0.8785, F-static = 66.5391, P-value = 0.0000, Estimation of the error variance = 0.0009						
Nighttime kW/capita of Tokyo	0.8544	0.0000	-0.0000	-0.0366	-0.0003	-0.0023
P<0.05	(0.8743~ 1.0878)	(0.0000~ 0.0000)	(-0.0010~ 0.0010)	(-0.0448~ -0.0059)	(-0.0633~ 0.0365)	(-0.0366~ -0.0084)
R^2 = 0.9265, F-static = 115.8964, P-value = 0.0000, Estimation of the error variance = 0.0004						

Table 5: Coefficient rates and stats summaries of models for Tokyo

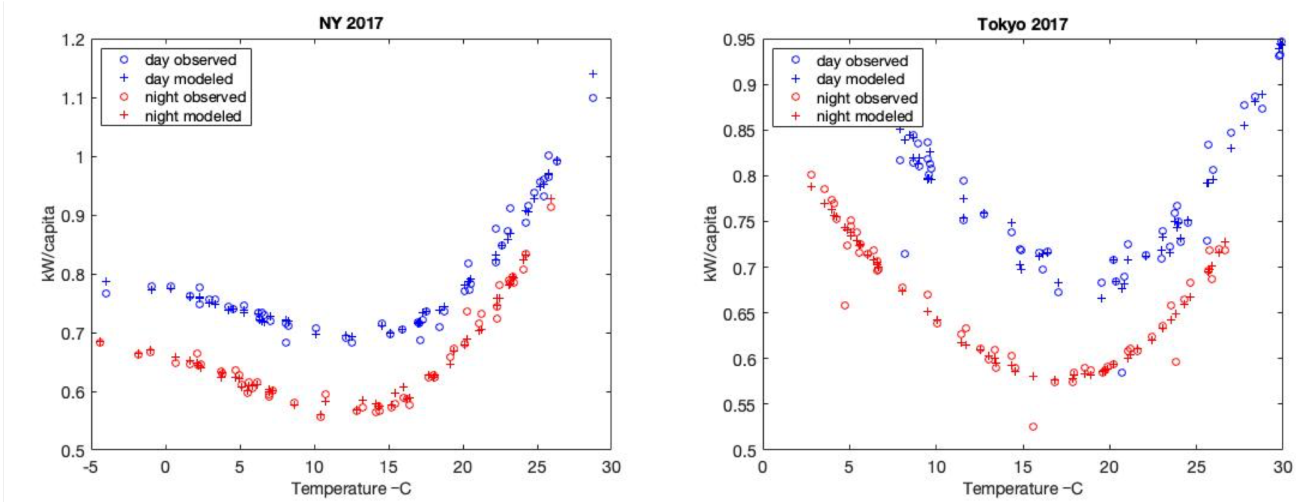

Figure 6: Observed (o) kW/capita of daytime (blue) and nighttime (red) in scale of temperature and modeled (+) kW/capita of daytime and nighttime in scale of temperature

4) Forecast future electricity consumption based on IPCC prediction

This section tries to predict the amount of increasing of electricity consumption based on annual general model which made in section 2.2). Figure 7 shows annual averaged fractional increasing of kW/capita against temperature rising. This figure is made with a simple assumption that temperature increases simultaneously through whole time. This figure shows that effects of temperature rising is larger for NYC than for Tokyo. This is caused by both of relatively higher temperature elasticity of kW/capita in summer in NYC and lower temperature elasticity of kW/capita in winter in NYC. Because of temperature rising, both NYC and Tokyo are forced to spend more electricity in summer season, but, as showed in section 2.2), people in Tokyo mainly uses electricity for heating their buildings so Tokyo can reduce electricity consumption because of benefit from more moderate winter season.

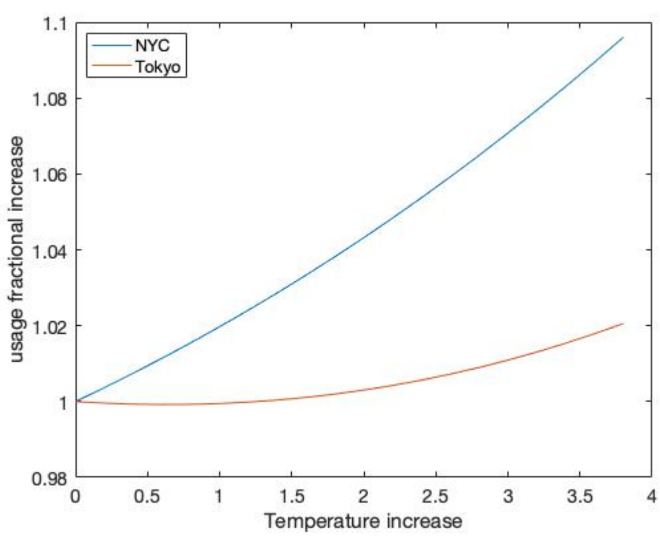

Figure 7: Usage fractional increasing of kW/capita in scale of temperature increasing

Intergovernmental Panel on Climate Change (IPCC) report that reflecting the long-term warming trend since pre-industrial times, observed global mean surface temperature for the decade 2006–2015 was 0.87°C (likely between 0.75°C and 0.99°C) higher than the average over the 1850–1900 period with very high confidence. And, estimated anthropogenic global warming is currently increasing at 0.2°C (likely between 0.1°C and 0.3°C) per decade due to past and ongoing emissions with high confidence. As a result of these observations, IPCC predicts that human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C, and global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. (IPCC, 2018) According to this prediction from IPCC reports, average temperature will increase 0.5ºC in 2030 comparing with 2017. Thus, the values of kW/capita of NYC approximately increase by 1% although the value of Tokyo almost does not change. The increasing 1% of kW/capita means that total electricity consumption also increases by 1%. The amount of total electricity consumption in NYC in 2017 was 52,266.1098GWh, thus, 1% of it equals to 522.661098GWh.

The value of average emission can be assumed from information of sources of actual electricity production in area which NYC locates. The New York Independent System Operator (NYISO) reports electric energy production in New York State by Fuel Source in downstate New York in 2017. According to the report, electricity demand in downstate New York in 2017 was covered by Oil (0.1%), Dual fuel (Gas and Oil; 66.8%), Gas (3.0%), Nuclear (23.4%), Hydro (3.7%), Hydro pumped storage (0.5%), and Other Renewables (2.4%). (NYISO)

And, Life Cycle Assessment (LCA) of electricity is commonly applied for measuring the degree of emissions from whole processes from mining sources to actually generating electricity. Turconi calculated values of LCA of gas, oil, coal, hydro and nuclear based on 33 LCA publications including 167 case studies of all main electricity generation technologies, representing 98% of global electricity generation in 2008. According to this paper, each source emits CO_2 kg per generating MWh that natural gas (380-1000), oil (530-900), coal (660-1050), hydro (2-20) and nuclear (3-35). (Turconi et al, 2013)

Based on the shares of energy sources and calculation from Turconi, the range of emission from additional demand of electricity (522.661098GWh) in future can be simply assumed. Weighted average of emission in NYC in 2017 is acquired by weighted average that 495382.6kg/GWh. And, the possible range is from 316391.1kg/GWh to 674374.1kg/GWh. So, when the additional demand of electricity is covered by same sources in 2017, the additional demand causes 258917.2143 metric ton of CO_2.

5) Forecast future electricity consumption considering with daytime and nighttime cycle

Pierre-louis et al reported that summer nights have warmed at nearly twice the rate of days, with overnight low temperatures increasing 1.4 degrees Fahrenheit per century since 1895, when national temperature records began, compared to a daytime high increase of 0.7 degrees per century. (Nights have warmed faster than days during other seasons, too.) based on the data from National Oceanic and Atmospheric Administration. (Pierre-louis et al, 2018)

6) Implications from quantitative analysis

This section focused on analyzing characteristics of NYC and Tokyo from a perspective of quantitative analysis like making graphs and models. These graphs and models show that i) even two cities which are well developed and under not so different climate condition like NYC and Tokyo have different characteristics of electricity consumption reflecting various factors like human behaviors and ii) a city which uses electricity for both heating and cooling their buildings can offset the effects of global warming which causes increasing the demand of electricity in summer season by decreasing demand in winter season.

3. Social factors of electricity demand

Electricity demand is influenced by various factors. Weather condition is definitely one of crucial factors which influences the amount of electricity demand. However, social factors also affect electricity demand a lot. This section shows some important factors which has impact on electricity demand for considering the effect of climate change on electricity demand more deeply.

1) Vintage of buildings

There are many papers which search on relationships between electricity consumption and vintage of buildings. Intuitively, older buildings seem to spend more electricity because they tend to have older inefficient facilities like older air conditioner. But, the amount of electricity consumption depends on various factors like size of building, dwellings of buildings and rate of energy source (old buildings tend to use rather gas than electricity for heating). (Whyatt, 2013) In fact,

Aksoezen et al collected the average energy consumption level of all buildings with the same age from data on 20,802 buildings in the City of Basel in the canton of Basel-City. They showed that both buildings constructed over the past 30 years and buildings constructed more than 100 years ago have a lower average consumption level than the rest of the stock. (Figure 7)

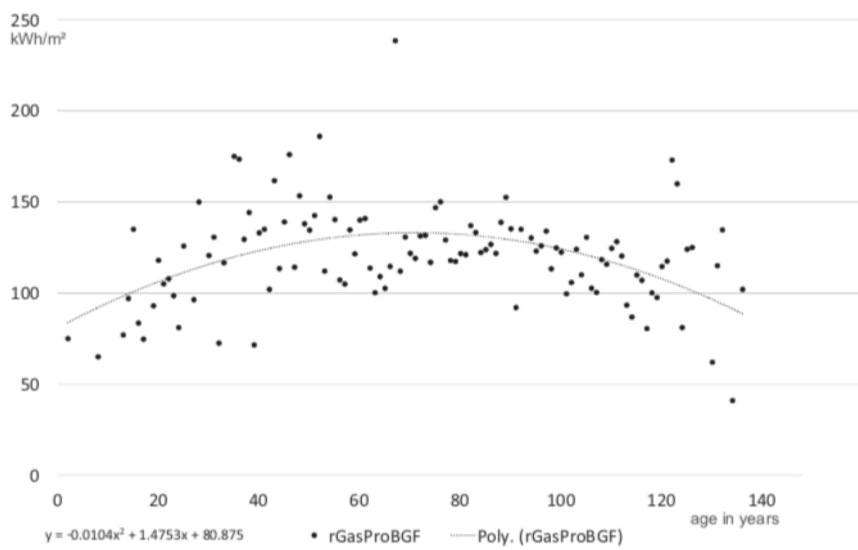

Fig. 11. Average energy consumption level of all buildings with the same age. Both buildings constructed over the past 30 years, and buildings constructed more than 100 years ago, have a lower average consumption level than the rest of the stock. The significant correlation between energy consumption and construction age can be described by a polynomial function (dotted line).

Figure7: Average energy consumption level of all buildings with the same age (Aksoezen et al, 2015)

In this manner, electricity consumption is influenced by various factors, so it is so difficult to forecast the amount of future electricity. On the other hand, there are some characteristics which certainly happen in near future. A paper which focuses on relationship between building vintage and temperature response in residential buildings in part of California, and shows that relatively new buildings, which built in 1970–2000, have a statistically significantly higher temperature response. This means new buildings use more electricity in response to higher temperature than old buildings, which built before 1970. This means that the average temperature response is expected to go up as new buildings are added and peak electricity load will also increase because residential buildings have higher temperature response even with climate held constant. (Howard, 2012)

4. Result and Policy implications based on this analysis

Considering implications acquired from section 2. and 3. that: i) even two cities which are well developed and under not so different climate condition like NYC and Tokyo have different characteristics of electricity consumption reflecting various factors like human behaviors and ii) a city which uses electricity for both heating and cooling their buildings can offset the effects of global warming which causes increasing the demand of electricity in summer season by decreasing demand in winter season and iii) as cities develop, the average temperature response of the cities is expected to go up, next three general results can be assumed: i) supply-demand in peak time in summer might be tighter because of general temperature rising and going up of temperature response of cities and ii) the gap of required capacity between summer and winter becomes larger in cities which spend different energy sources for cooling and heating and iii) effect of increasing of kW/capita in night time is enough big not to ignore the effects. Considering these factors, this paper conclude that two actions are need for mitigating and adopting metropolitans to future warmed world: Increasing capacities of low emission electricity in night time and decreasing the gap of required capacity between summer and winter by electrification.

1) Increasing capacities of clean electricity in night time

As discussed above, Demand supply gap of electricity potentially becomes tighter especially in night time. Thus, increasing capacity of low-emission electricity, which can generate electricity efficiently with low emissions, is important for decreasing GHG emissions in future. Thermal plants (including gas, oil, coal and other fuels), hydro, nuclear and batteries are representative candidates of sources which can generate in night time.

Increasing the amount of batteries should be a candidate for increasing night time capacity. As described in 3.2), there is a certain demand gap between weekday and weekend, so there is so much potential for batteries to smooth the gap of supply and demand of electricity not only between daytime and night time. However, increasing only batteries themselves does not reduce emission. Hittinger et al modeled the economic and emissions effects of bulk energy storage. And, they calculated the profits under two scenarios (perfect and imperfect information about future electricity prices), and estimated the effect of increasing the amount of storage on net emissions of CO_2 in the United States. And they found that storage increases CO_2 emissions compared with the emissions from electricity generation, ranging from 104 to 407 kg/MWh of delivered energy depending on location, storage operation mode, and assumptions regarding carbon intensity. (Hittinger et al, 2015)

There are two mechanisms which storages cause additional emissions: 1) storage tends to charge at night during off-peak hours and discharge during peak afternoon or evening periods. In many areas of the U.S., the marginal electricity generator at night is often a coal plant and the marginal generator during peak periods is a natural gas plant. This means that storage is displacing natural gas generated electricity with coal generated electricity. 2) storage technologies cause energy losses as they store and recover energy. This inefficiency means that storage reques the system to generate extra electricity and emissions to compensate for these losses. (Hittinger et al, 2015) In this manner, battery owners have incentives to purchase cheap electricity even though the electricity is generated from high emission plant like coal plant from economical perspective. And, Hittinger et al clearly shows that CO_2 emission increase if we increase the amount of batteries in areas which do not have surplus power generated from low emission generators. (Hittinger et al, 2015) This means that as like Kyushu area, which is southern part of Japan and the area has too much surplus power which is generated from Solar PV in daytime, can reduce emission from adding battery capacity in the area. And the utility company in the area first

experienced in Japan that the company has ordered owners of Solar PV to stop generating for keeping the balance of demand and supply of electricity. (Nikkei, 2018) But,
Calculating the marginal value of potentially reduced emission by displacing coal electricity with nuclear.

2) Decreasing the gap of required capacity between summer and winter by electrification

There are two big benefits for decreasing the gap of required capacity between summer and winter that: 1) it decreases the cost of fixed cost loss for generators and 2) it reduces emissions by replacing utility gas for electricity. Big gap of required capacity between summer and winter causes to increase the cost of electricity because all types of generators cost owners for fixed cost whether the owners use these facilities or not. This means that

5. Future works

There are many things to do for making them clearer that characteristics which decrease the amount of electric consumption under warmed future. First of all, confirming characteristics of other world metropolitans under other climate conditions like Paris and London definitely helps to verify tips for electricity consumption. In addition, more precise values of future emission can be calculated by considering trends of sources of electricity. This means that cities which have high solar PV penetration rate have higher potential for reducing CO_2 emission by electrification.

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Signature

大瀧 拓馬