Modeling the response of hourly electricity demand to climate conditions in Japan

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Overview

In this research, we attempted to acquire reliable temperature response functions (TRFs), which measure electricity consumption as a function of temperature, for hourly electricity consumption in 10 Japanese regions. The energy sector plays an important role in climate change, for both mitigation sand adaptation[1], and both the energy supply and demand systems are expected to be affected by climate change[2]. It is therefore important to understand the impacts of climate change on energy systems. One of the expected impacts on the energy sector is that rising ambient temperature will decrease heating demand in the cold season and increase cooling demand in the hot season[3]. This impact will be especially pronounced in the power sector[4]. However, because electricity demand represents a timely human response to environmental conditions that are determined by multiple factors, changes in demand in the future might be amplified by frequent extreme weather events. Therefore, to predict future electricity consumption under climate change as well as project the capacity and fuel requirements of electricity generation, we need to provide reliable TRFs based on short-term observations. There are two main challenges to acquiring precise TRFs. First, we need to consider multiple factors other than temperature, such as other climatic factors and the daily cycle of human activities. Second, we need to capture nonlinearities and interaction relationships between variables in the model. We constructed models by using non-parametric regression technique called multivariate adaptive regression splines (MARS)[5][6], which consider multiple factors, including climatic conditions and the daily cycle of human activity. The constructed models are high quality in terms of fit, generalization capability, and accuracy in simulating TRFs. On the basis of simulations conducted by using the constructed models, we identified two distinct daily TRFs (daytime and night-time). We also present a method to provide simple parameters to other models by approximating the TRFs by piecewise linear functions. In addition, we found a significant impact of humidity on electricity consumption under high-temperature conditions by using other simulations based on the same models. The proposed method is recommended for identifying reliable TRFs; this identification is indispensable for predicting the impacts of future electricity consumption under climate change.

Methods

The target areas were the jurisdictions of 10 major electric power companies (EPCs) in Japan. We constructed regression models that explain hourly electricity consumption by using multiple variables, such as climatic indicators and indicators of human activity for each EPC. The hourly data observed in fiscal year 2016 were used for model construction and those in fiscal year 2017 were used for model verification. The explained variable is the hourly power supply-demand data provided by the EPCs. The explanatory variables are 6 meteorological indicators, 2 thermal comfort indices derived from meteorological indicators, and 4 variables that represent human activity level. For model construction, we used the MARS non-parametric regression technique[5][6]. MARS renders it possible to construct a flexible yet highly generalizable model that models nonlinearities and interactions between variables while automatically selecting the important variables. By using the constructed models, we simulated the levels of electricity consumption at different temperatures while controlling for the other variables. We present hourly TRFs for a 24-h period and specified the 2 distinct TRFs in the 24-h period. Because TRFs should be simple enough to be applied to other models, we approximated them with a piecewise linear function and acquired parameters such as coordinates of the breakpoints and coefficients of the regression lines. We also simulated TRFs at different humidity levels to determine the effects of humidity.

Results

Figure 1 shows the performance of the constructed models. Not only the black dots (in-sample results) but also the blue dots (out-of-sample results) scatter around 45 degrees diagonal of each panel, and their regression lines are almost identical. The in-sample results are the scatter plots of observed and predicted values based on the data used for model construction and out-of-sample results are the same plots based on the data NOT used for model construction. Therefore, the constructed models are of high quality in terms of both fit and generalization capability. Figure 2 shows the simulated hourly TRFs in each EPC. The colored lines show the simulated TRFs for each hour and the black dots show the observed values. The models well present the relationship between temperature and electricity consumption, because the lines are well matched with the observations. The reddish lines are concentrated in the upper side of each panel, whereas the blueish lines are concentrated in the lower side, with relatively few values between these lines. In this case, the reddish TRFs are for daytime hours (around 10:00 to 18:00), the bluish TRFs are for night-time hours (around 1:00 to 5:00), and the others are the TRFs for the transition time from day to night and night to day.

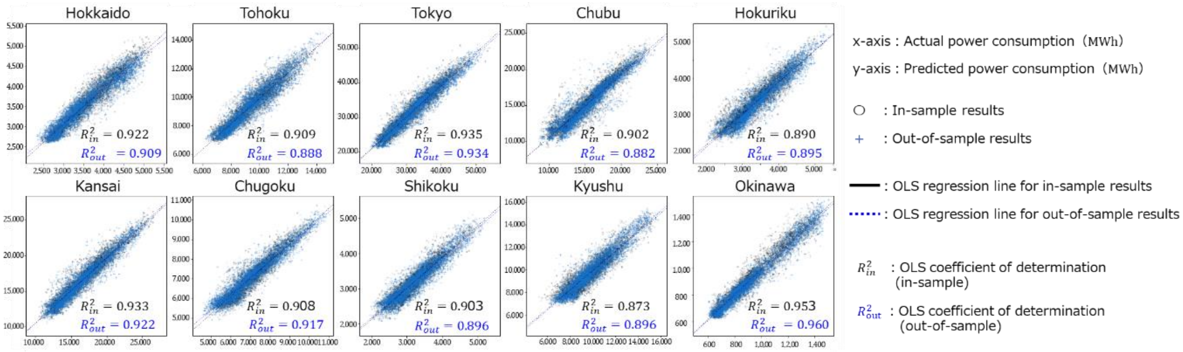

Figure 1 Performance of the constructed models

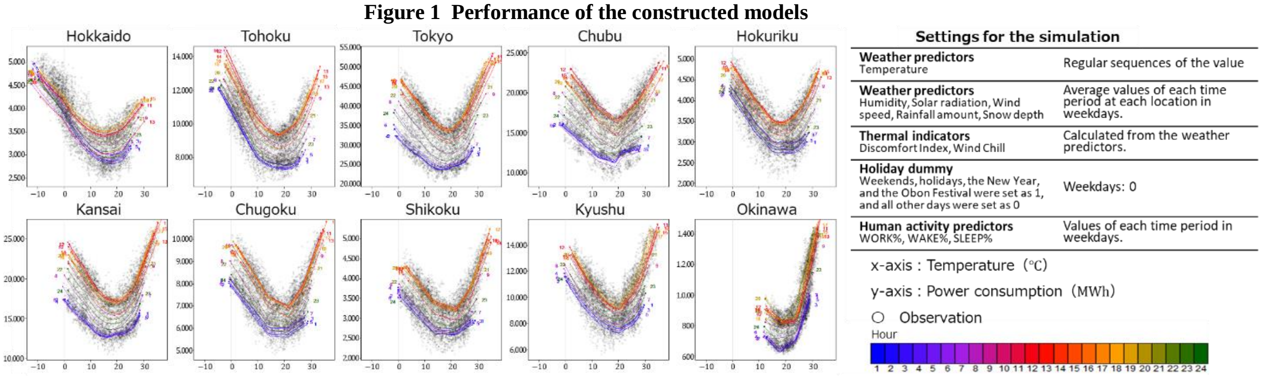

Figure 2 Hourly TRF simulations

Figure 3 shows the process of approximating TRFs, taking Tokyo as an example. The two simulated distinct TRFs acquired for daytime and night-time are shown as the colored lines in Figure 3b. The two simulated TRFs well represent the obserbation shown in Figure 3a. We approximated the specified TRFs by a piecewise linear function (Fig. 3c), which made it possible to provide a simple formula and parameters, such as coordinates of the breakpoints and coefficients of the regression lines, to other models (Fig. 3d).

In addition, by simulating TRFs at different humidity levels, we found that humidity affects electricity consumption markedly when the temperature is high in all of the EPCs except Okinawa, and that the balance point temperature (the temperature at the bottom of the V-shaped TRFs) decreases as humidity increases. This indicates that, when humidity is high, the power consumption for cooling begins to increase at lower temperatures.

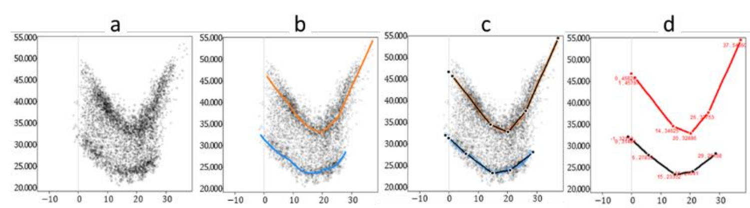

Figure 3 The approximation process, using Tokyo as an example

Conclusions

We constructed a regression model by using MARS and considering multiple factors. The constructed models are of high quality in terms of fit, generalization capability, and accuracy in simulating TRFs. From simulations using the constructed models, two distinct TRFs were identified in one 24-h period (i.e., each day). Although regional differences in TRFs have often been discussed in previous studies (e.g.[4]), the studies that have discussed time (i.e., hourly) differences in TRFs were not found. To predict the fluctuation of future electricity consumption under climate change, time differences should also be considered. In addition, the model made it possible to understand the effect of climatic factors other than temperature. Humidity under high temperatures was found to have a substantial impact and should not be ignored when predicting the impacts of future electricity consumption under climate change. The proposed method should be useful for identifying TRFs. As a future contribution, we are developing a method to construct a single regression model that explains electricity consumption for the whole of Japan by considering region-specific and time-varying factors simultaneously.

References

[1] R. Schaeffer et al., “Energy sector vulnerability to climate change: A review,” Energy, vol. 38, no. 1, pp. 1–12, Feb. 2012.

[2] T. K. Mideksa and S. Kallbekken, “The impact of climate change on the electricity market: A review,” Energy Policy, vol. 38, no. 7, pp. 3579–3585, Jul. 2010.

[3] M. Auffhammer and E. T. Mansur, “Measuring climatic impacts on energy consumption: A review of the empirical literature,” Energy Economics, vol. 46, pp. 522–530, Nov. 2014.

[4] L. Wenz, A. Levermann, and M. Auffhammer, “North–south polarization of European electricity consumption under future warming,” Proceedings of the National Academy of Sciences, p. 201704339, Aug. 2017.

[5] J. H. Friedman, “Multivariate Adaptive Regression Splines,” The Annals of Statistics, vol. 19, no. 1, pp. 1–67, Mar. 1991.

[6] Stephen Milborrow Derived from mda:mars by Trevor Hastie and Rob Tibshirani. Uses Alan Miller’s Fortran utilities with Thomas Lumley’s leaps wrapper, “earth: Multivariate Adaptive Regression Splines. R package version 5.1.1.,” 2019. [Online]. Available: https://cran.r-project.org/package=earth.