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Reproducing solar curtailment with Fourier analysis using Japan dataset

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Abstract

Curtailment of variable renewable energy increases the Levelized Cost of Energy (LCOE), which is the tool often used to compare its profitability against traditional energy sources. Recently, the Kyushu Region of Japan had to curtail some of its solar production to meet energy balance. As many countries increase their solar energy production, curtailment will be inevitable. It is therefore important to develop methodologies to calculate it. In the case of Japan, curtailment can easily be estimated using hourly data. However, such data is unavailable in other countries. In this study, a methodology to reproduce curtailment using known periodicity and statistical data is presented. Insights were initially generated by simulating future curtailment scenarios of Kyushu to extract the factors that affect curtailment. Fourier analysis was used to identify the periodicity of demand and solar production. The Fourier representation was simplified using the identified factors. Along with statistical data, the demand and solar data were approximated and the curtailment was reproduced. Results show that curtailment can be closely reproduced using the proposed methodology on a yearly and monthly level. Further research is necessary to test the methodology for other conditions like having different climate, varying daily fluctuations, and other human-related fluctuations.

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Keywords: Solar curtailment; Solar installation; Energy balance simulation; Fourier analysis; Fourier approximation

1. Introduction

In Japan's fifth Strategic Energy Plan, the government reiterated its commitment to the projected energy mix for 2030, where renewable energy will comprise 22%–24% and solar has a 7% contribution [1]. In order to achieve the solar target, Japan is promoting research and development, Feed-in-Tariff (FiT), and competitive procurement prices.

Located closer to the equator, Kyushu has higher solar potential relative to the rest of Japan. Coupled with cheaper land, there has been an increasing solar investment in the region. Kyushu ahas six nuclear power plants

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(NPP), and as of June 2018, four units with a total capacity of 4.140 GW is fully operational [2]. Given the solar potential and existing NPPs, Kyushu can offer non-carbon energy source to the main island of Honshu.

Despite the increased solar and nuclear penetration, as seen in Fig. 1, Kyushu is still heavily dependent on thermal power plants. Additional solar investment is needed to reduce the dependence on thermal power plants. However, in October 2018, Kyushu was forced to curtail some of the solar production. Recent data from March 2019 shows more frequent curtailment. Fig. 2 shows that on top of charging the pumped hydro storage, thermal production was reduced, but the effort was insufficient to meet the energy balance. Curtailment will eventually increase in frequency and magnitude since there are 8 GW of additional solar installation scheduled for connection on top of the currently installed capacity of roughly 8 GW by early 2019 [3].

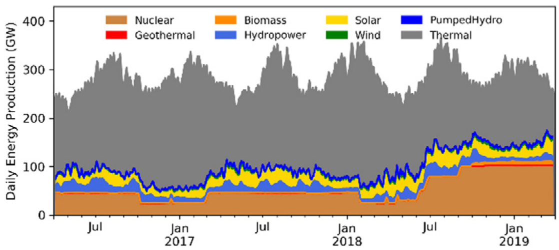

Fig. 1. Energy Balance of Kyushu (FY 2016–2018) [4].

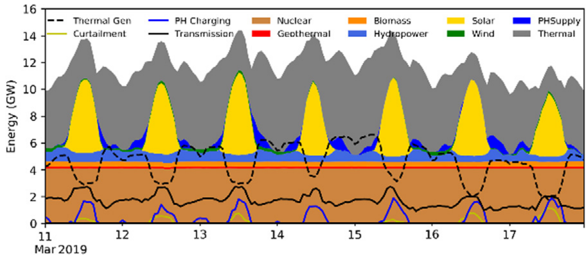

Fig. 2. Recent solar curtailment in Kyushu.

Several countries with high variable renewable energy installation are also experiencing the curtailment issues of Kyushu. Curtailment happens when (1) is true. Efforts to reduce curtailment are mainly focused on balancing the four components. The mismatch of PV supply and electricity demand and the limitation of other sources to respond to rapid changes limits the large scale integration of solar PV [5]. Possible solutions include transmission [6,7], storage [8], Demand-side Management (DSM) [9], increasing generator flexibility [5,7] and PV design that matches demand [10].

$$S_{baseload} + \min S_{flexible} + S_{solar} - demand > 0 \tag{1}$$

Despite all these efforts, curtailment is inevitable and it is essential in estimating the total energy production that can be effectively used since this reflects on the Levelized Cost of Energy (LCOE). In the case of Japan, hourly data is available which makes the calculation easier. For some countries, data are not collected nor published; thus, calculating curtailment will be difficult. The case of Kyushu is a prime candidate in studying curtailment since it has the anticipated increase in solar installation and has more than sufficient data to extract essential information.

This study proposes a methodology to reproduce curtailment information using known periodicity and statistical data. An analysis of the future curtailment scenario is presented where curtailment is characterized. Fourier approximation of the significant segments of demand and solar production is approximated to reproduce the curtailment. Finally, an evaluation of the reproduction is presented where significant data are identified to an acceptable level of reproduction. Possible applications are also presented.

2. Methods and data

The data were collected from the website of Kyushu Electric Company, where the hourly information about demand, generation, transmission, and curtailment are published [4]. Transmission is considered as part of the total load. Pumped hydro storage is seen as both generator and load depending on its operation. Although the baseload could change within the year, the baseload was fixed to its maximum capacity.

In the simulation, all the other data were considered as fixed except for solar and thermal production. The simulation for the whole study focused on the 2018 hourly data. The solar installation was treated as the controlled variable, and the thermal generators produce the remaining demand. Solar energy is preferred unless the lower limit of the thermal plant is reached. The simulation used 15% minimum production for the thermal plant. If the limit is reached, the excess solar generation will be curtailed. The energy balance calculations were done using Python for Power System Analysis (PyPSA) [11].

Initially, the installed capacity was increased until 30 GW to visualize the impact of increasing installed capacity to the curtailment. The analysis then focused on 2 GW increments from the current installation of 8 GW to the scheduled installation of 16 GW. Monthly, weekly, and daily data were analyzed to extract information crucial to curtailment.

Taking into consideration the identified factors that affected the amount of curtailment, the demand and solar generation were first approximated using Fourier approximation and statistical data. Once all the essential data were approximated, the curtailment was recomputed using the same set of data and assumption used in the initial simulation. Finally, the results of the simulation using the actual data and reproduced data were compared and analyzed.

3. Kyushu solar curtailment analysis

It can be seen in Fig. 3 that initially, as PV installation increases, the production and consumption are aligned. After a certain point, there is an increasing gap between the PV production and consumption which represents increasing curtailment. At the anticipated installed capacity of 16 GW, it is expected that around 23% of the annual PV production will be curtailed. It is essential to understand the source of the curtailment to determine the estimation compromises.

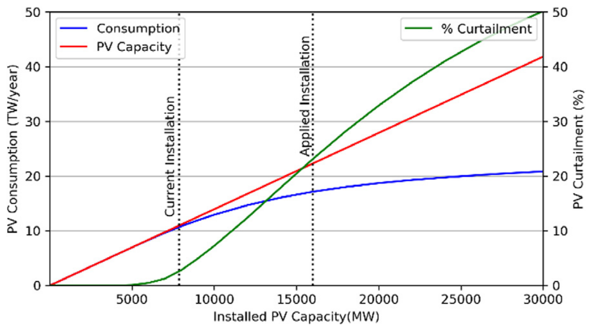

Fig. 3. Simulated amount of curtailment using 2018.

PV production in Japan peaks in summer and gradually decreases until winter as seen in Fig. 4. Generation reduces late spring due to rainy weather. The demand of Kyushu also peaks in the summer and winter, but in contrast to the supply, there is less demand in spring and autumn. Based on the data seen in Fig. 4, the difference in supply and demand during fall and spring led to higher curtailment rate. This shows the importance of focusing on the period with the highest mismatch in estimating curtailment.

Less demand in the weekend often leads to more curtailment during this period. In terms of frequency, curtailment also starts to manifest in the weekend and then eventually in the weekdays. Weekly variations compound the seasonal changes in demand resulting for curtailment to initially occur on the weekends of spring and autumn. This eventually spreads to other seasons as solar installation increases. Weekend fluctuations should also be well represented.

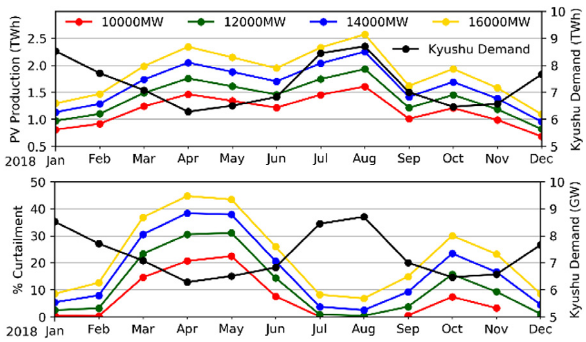

Fig. 4. Kyushu demand, PV production, and % curtailment.

The majority of solar production happens in the middle of the day. However, at higher solar installation, curtailment may begin even at the start of the day. Despite this, upon closer inspection, the majority of the curtailment still occurs between 9:00 and 15:00 at the projected 16 GW installation in Kyushu. The approximation should, therefore, put higher importance to this part of the day. The rest of the day is acceptable compromises when necessary.

4. Curtailment reproduction

4.1. Demand approximation

Initially, it was assumed that human behavior affects the demand curve. Therefore, the periodicity of human behavior should be considered. To utilize this periodicity, Fourier approximation is proposed. However, looking into the data reveals that each season has a different daily demand curve, which makes it challenging to identify the periodicity. To solve this problem, a segmented Fourier approximation was tested. The weekly periodicity was initially explored to appropriately divide the year. A Fourier Transform was used to identify the frequency components of each week. Using the magnitude of each frequency, K-means clustering was used to cluster the weeks into six segments.

It was observed that each segment has similar daily fluctuations. Another Fourier Transform was done to identify the frequency components of each segment. For each segment, seven harmonics representing the weekly and daily variations were selected. The 7th weekly harmonic coincided with the 1st daily harmonic. The DC component was also selected. It can be seen in the simplified cosine Fourier equation in (2) that the demand curve, for each segment, can be approximated using a DC offset (A_o), 6 weekly components, and 7 daily components. W_n and D_n is the ratio of the magnitude of each Fourier term using W_1 and D_1 as reference. The ratio of the components creates the overall shape of each model. B_0 and C_0 serves as the scaling factor for the weekly and daily components, respectively. Each frequency component has a corresponding phase shifts w_n and d_n based on the model.

$$demand\,(t) = A_0 + \mathrm{B}_0 \sum_{1}^{6} 2W_n \cos\left(\frac{2\pi}{168}\mathrm{n}t + w_n\right) + \mathrm{C}_0 \sum_{1}^{7} 2D_n \cos\left(\frac{2\pi}{24}\mathrm{n}t + d_\mathrm{n}\right) \tag{2}$$

Approximating demand using (2) requires three sets of data: the model that was initially developed, model assignment for each week, and available data where the model will be fitted. There are various ways to assign a model per week. For this implementation, prior knowledge was used. The models and model assignments provide the corresponding magnitude W_n and D_n and phase shifts w_n and d_n for each frequencies for each week.

The available data points were then used to identify the scaling components B_0 and C_0 of the model for each week. The current implementation requires four data points (9AM, 3PM, 6PM, and 9PM) per day due to periods with half-day cycle. This can further be reduced to twelve data points per week by sampling weekdays, Saturdays, and Sundays. Another option is to reconstruct the data points using statistical data like average consumption, the number of peaks, peak values, and valley values. Using the daily harmonics (second summation), the initial shape of the week was approximated by identifying A_0 and C_0 using Least Square Method. The average weekday data was initially used. The weekly harmonics (first summation), were then used to fine-tune the approximated signal by identifying B_0.

In order to maintain uniformity, the same methodology was used for all segments despite segment 1 having less accuracy as seen in Fig. 5. This was acceptable since there is less curtailment early in the year to have a significant impact on the curtailment calculation. The critical months in segment 2 and 3 (April, May, and June) were reproduced well. The weekend variations were also well represented.

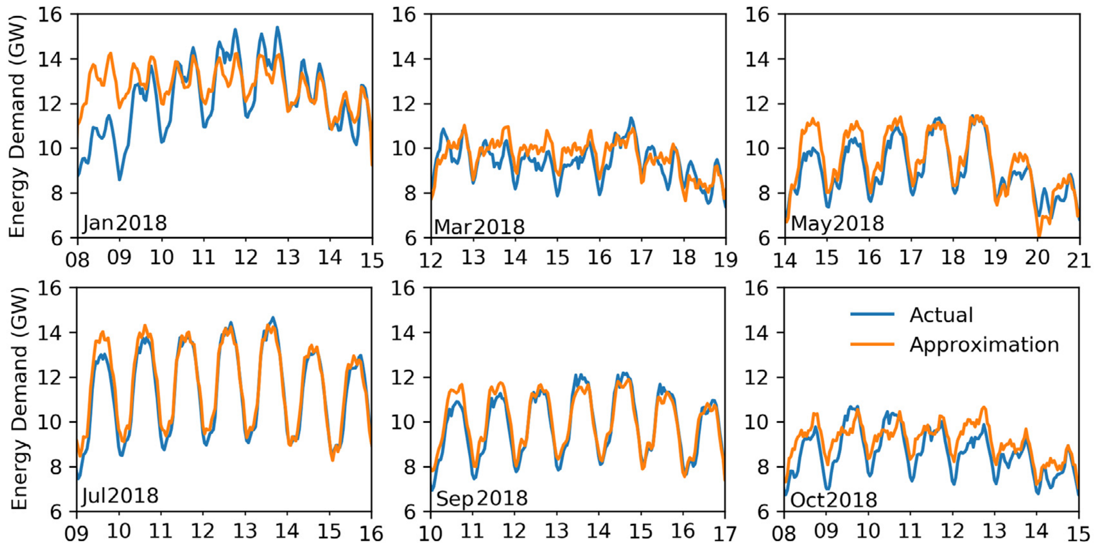

Fig. 5. Demand approximation for each of the six segments.

4.2. Solar approximation

Solar production does not have a periodicity that could be exploited. However, the general shape of solar production is the same. The solar generation can be approximated using a three-step process. First, Fourier approximation can be used to determine the shape. Second, the peaks can then be determined based on probability. Finally, using the peaks as an envelope, the peak of each curve can be used to approximate the actual solar production.

Results in Fig. 6(a) shows that the general shape can be reconstructed using three daily harmonics. Since the goal is to reproduce the curtailment, minor shape difference due to varying time for sunrise and sunset are acceptable compromises. This is acceptable since curtailment mostly happen from 09:00 to 15:00. Since solar production is stochastic, past solar radiation or peak data can be used to generate a probability distribution per month to reproduce the peaks. In this study, a discrete probability distribution per month was generated using the actual data. The distribution was then used to randomly generate the peaks shown in Fig. 6(b). Using the peak as an envelope, as shown in Fig. 6(b), the solar generation was approximated with the Fourier approximation of the shape.

4.3. Curtailment reproduction

Using the baseload and flexible generator values used in the initial analysis of Kyushu and the approximated demand and solar production data, the curtailment was recalculated. Fig. 7 shows that the reproduced curtailment values closely resemble the initial simulation with different margins of error depending on the installed capacity. Fig. 8 shows that the reproduced signal can also be used to analyze monthly curtailment.

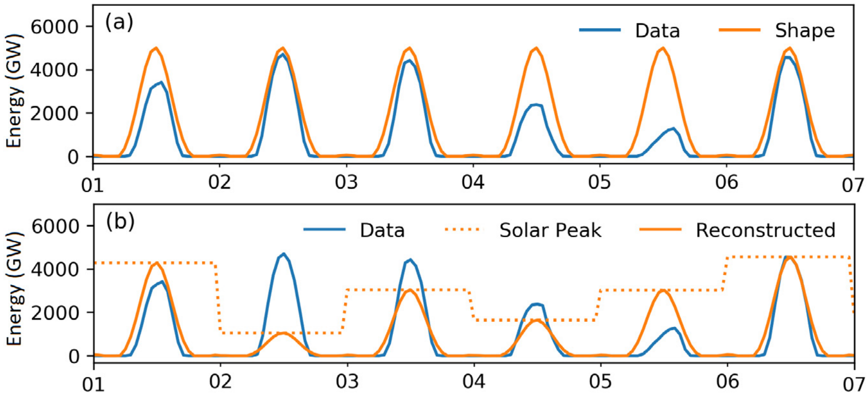

Fig. 6. Solar approximation. The shape was reconstructed in (a), and the peaks were generated and the two information were combined in (b).

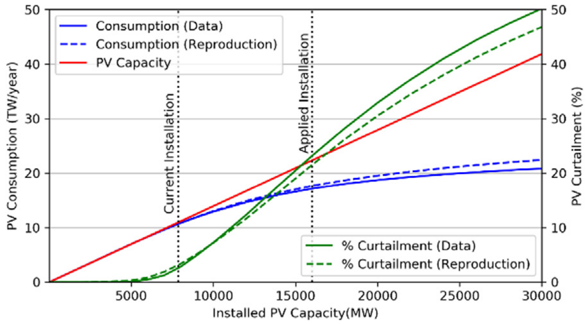

Fig. 7. Comparison of the curtailment calculation.

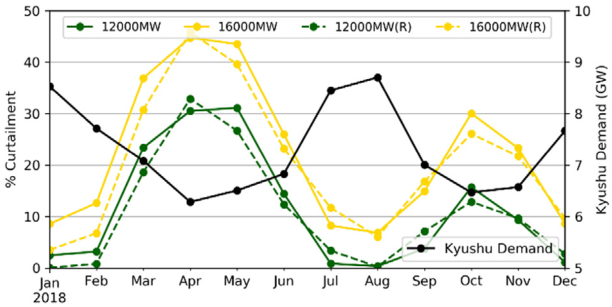

Fig. 8. Comparison of the seasonal curtailment.

5. Conclusion

A Fourier approximation methodology was presented to reproduce curtailment. The case of Kyushu was analyzed to extract factors that affect curtailment, and three major considerations were highlighted. First, curtailment occurs in the periods with the larger mismatch between supply and demand. Second, weekend fluctuations should be considered. Finally, focusing on the energy balance between 09:00 and 15:00, where the most of curtailment occurs, is sufficient.

Following the three consideration, demand was modeled using Fourier approximation where 15 harmonics were sufficient to approximate the demand. The model can be used along with model assignment for each week, and existing data where the model will be fitted. The solar production was approximated using Fourier approximation for the shape and solar peak probability distribution for the peaks. Multiplying the two approximates the solar production.

Finally, the curtailment can be reproduced by calculating the energy balance for each hour using the approximated demand and solar curve, and known data about the flexible load and baseload. The current reproduction has up to 3% error depending on the installed capacity. This methodology can be used to reproduce curtailment for countries where the statistical or specific data can be collected without resorting to gathering hourly data.

References

[1] Ministry of Economy Trade and Industry. Japan'S Fifth Strategic Energy Plan (Provisional Translation). Ministry of Economy Trade and Industry; 2018, Retrieved from https://www.enecho.meti.go.jp/en/category/others/basic_plan/5th/pdf/strategic_energy_plan.pdf.

[2] Kyushu Electric Company. Kyushu electric company group annual report 2018. 2018, Retrieved from http://www.kyuden.co.jp/var/rev0/0149/3830/c7ujptmy_all.pdf.

[3] Kyushu Electric Company. Renewable energy application (Japanese). 2019a, Retrieved from http://www.kyuden.co.jp/effort_renewable-energy_application.html. [28 March 2019].

[4] Kyushu Electric Company. Supply and demand information (Japanese). 2019b, Retrieved from http://www.kyuden.co.jp/wheeling_disclosure.html. [28 March 2019].

[5] Denholm P, Margolis RM. Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies. Energy Policy 2007;35(9):4424–33. http://dx.doi.org/10.1016/j.enpol.2007.03.004.

[6] Hart EK, Stoutenburg ED, Jacobson MZ. The potential of intermittent renewables to meet electric power demand: Current methods and emerging analytical techniques. Proc IEEE 2012;100(2):322–34. http://dx.doi.org/10.1109/JPROC.2011.2144951.

[7] Martinot E. Grid integration of renewable energy. Ann Rev Environ Resour 2016;223–54. http://dx.doi.org/10.1146/annurev-environ-110615-085725.

[8] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. http://dx.doi.org/10.1016/j.rser.2015.01.057.

[9] Janko SA, Arnold MR, Johnson NG. Implications of high-penetration renewables for ratepayers and utilities in the residential solar photovoltaic (PV) market. Appl Energy 2016;180:37–51. http://dx.doi.org/10.1016/j.apenergy.2016.07.041.

[10] Myers KS, Klein SA, Reindl DT. Assessment of high penetration of solar photovoltaics in Wisconsin. Energy Policy 2010;38(11):7338–45. http://dx.doi.org/10.1016/j.enpol.2010.08.008.

[11] Brown T, Hörsch J, Schlachtberger D. PyPSA: Python for power system analysis. Open Res Softw 2017. http://dx.doi.org/10.5334/jors.188.