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Evaluation of solar radiation abundance and electricity production capacity for application and development of solar energy

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Abstract

This study was undertaken to analyze solar radiation abundance to ascertain the potential of solar energy as an electrical energy resource. Local weather forecasting for predicting solar radiation is performed using a meteorological model MM5. The prediction results are compared with observed results obtained from the Japan Meteorological Agency for verification of the data accuracy.

Results show that local weather forecasting has high accuracy. Prediction of solar radiation is similar with observation results. Monthly average values of solar radiation are sufficiently good during March–September. Electrical energy generated by photovoltaic cells is almost proportional to the solar radiation amount. Effects of clouds on solar radiation can be removed by monthly averaging. The balance between supply and demand of electricity can be estimated using a standard curve obtained from the temporal average. When the amount of solar radiation every hour with average of more than 100 km radius area does not yield the standard curve, we can estimate the system of storage and auxiliary power necessary based on the evaluated results of imbalance between supply and demand.

Keywords: Solar radiation; Clouds; MM5; Solar energy.

1. Introduction

The world's modern day energy demands are still met largely from fossil fuels such as coal, oil, and natural gas. Regarding total energy demand, the share of fossil-fuel derived energy is around 80%. The remainder is supplied by nuclear and renewable energy of around 20% [1, 2]. Combustion of fossil fuels to generate electricity produces atmospheric CO_2 emissions. In 2005, total CO_2 emissions were 26.6 billion tons. More than 41% of those were produced from fossil fuels consumed throughout the world. That figure is expected to increase to 46% by 2030. CO_2 gas in large amounts is released to the atmosphere, constituting a primary cause of global warming [1, 3, 4]. The Kyoto Protocol, which is part of the United Nations Framework Convention on climate change, has the main objective of extracting firm commitments from developed countries for reducing their greenhouse gas emissions [5-7].

In addition, fossil-fuel derived energy is limited and nonrenewable energy, so that fossil-fuel derived energy resources are becoming increasingly scarce and expensive. However, energy demand will continue to increase worldwide. The annual growth rate of energy consumption is around 1% in developed countries and 5% per year in developing countries [8, 9]. When global energy production is primarily and continuously dominated by fossil fuels, an energy crisis will occur in the future. Therefore, renewable energy resources must be developed in each country. Several countries use nuclear energy as a primary energy source. Although nuclear generation does not directly produce atmospheric CO_2 emissions, it can cause severe damage to human life and the environment. It engenders problems of severe pollution and disposal of radioactive waste [1, 10]. The accident at Japan's Fukushima Daiichi nuclear power plant damage exerted a negative impact on the continuity of life and residents within a 30 km radius from the nuclear plant. They are still residing in more distant areas to avoid radiation exposure.

Utilization of fossil fuels and nuclear energy present severe environmental impacts. Those can be reduced by replacing them with renewable energy resources such as solar energy [8, 11, 12]. The demand for photovoltaic facilities has increased rapidly in recent years. The total cumulative capacity installed increased from 4,600 MW on 2008 to 16,000 MW in 2010 in Europe [13], and from 333 MW in 2006 to 2,036 MW in 2010 in the Asia–Pacific region [14]. In the United States, the annual growth rate of solar energy (PV and concentrating solar power) was around 22% in 2010 [15]. In Japan, solar energy utilization constitutes about 0.4% of total energy consumption, with photovoltaic capacity of about 29 W/capita or 9.7 KW/km^2 in 2010. Energy consumption has been dominated by that of nuclear energy, which accounted for about 25.2% of the total national energy consumption [16].

Solar energy is a clean energy resource offering enormous potential. However it presents difficulty in meeting the balance of demand and supply over a long-term period because it depends on the availability of solar radiation. Amounts of solar radiation vary in places depending on the geographical position, time of day, season, environmental characteristics, and local weather conditions. Consequently, the potential of solar energy differs in each place. In tropical areas, solar radiation is abundant, but in mid-latitude and high-latitude areas such as Japan, solar radiation is not necessarily sufficient throughout the year because its intensity and duration are limited during winter. In addition, weather conditions change over time, which causes the amount of solar radiation to vary over time. Moreover, energy demand will continue to increase concomitant with the escalation of human activity. Therefore, new technologies are necessary to estimate the balance between demand and supply in developing solar energy to its full efficient scale.

Japan, which is often in the path of typhoons and mid-latitude cyclones, has complex weather conditions induced by its many mountains, resulting in annual rainfall of around 1,700 mm/year. They strongly influence the solar radiation abundance. Many studies of solar energy have revealed that cloud conditions influence the amount of solar radiation, thereby influencing the output of photovoltaic power generation. Clouds and fog strongly affect the amount of solar energy received in a place. One effect of clouds on solar panels is to reduce the efficiency in output in certain parts of the world and in certain seasons. Dense cloud coverage that persists for several days can reduce solar panel output by more than 80% [17]. Consequently, cloud conditions are the most important factor in the application of photovoltaic facilities. Therefore, this study specifically analyzes the effects of clouds on solar radiation by temporal and spatial distribution to ascertain information about solar radiation amounts, which is indispensable for expansion of photovoltaic generation. We analyze a local weather forecast database with horizontal resolution of 2 km covering Gifu and Aichi prefectures, operationally forecasted using a mesoscale meteorological model MM5 every day from January 2006.

2. Methodology

2.1 Method and prediction condition

In this study, we temporally and horizontally estimate solar radiation during 2006–2010 using the local weather forecast database developed by the Natural Energy System Laboratory, Gifu University. The local weather forecast database is based on the MM5 meteorological model (http://www.mmm.ncar.edu/mm5/mm5-home.html), which describes the dynamics of the atmosphere in terms of atmospheric physics of several kinds, such as radiation physics, microphysics, boundary layer physics, and land surface physics [18]. The model comprises three domains: D1, a spatial resolution of 18 km covering the Japan archipelago; D2, a spatial resolution of 6 km including Kinki and Chubu districts; and D3, a spatial resolution of 2 km covering Gifu and Aichi prefectures (Figures 1, 2). An operational local weather forecast was started 1 June 2005, with proper authorization by the Japan Meteorological Agency (JMA). This is the first and the only weather forecasting service by a university in Japan. The forecasting was calculated during 48 hours and initialized at 12Z by the JMA Global Analyses with a horizontal resolution of 20 km and the condition of forecast calculation can be seen in

Table 1, although the first 12 hours of forecast lead time is not used for forecasts. It is available at the Gifu University website (http://net.cive.gifu-u.ac.jp).

This study comprises three phases. The first phase is to verify the accuracy of local weather forecasting by comparing its results (prediction) with observations obtained by JMA. The second phase is to analyze the amount of solar radiation based on temporal and spatial distributions derived from our database. The third phase is to calculate the electrical energy generated from solar radiation.

2.2 Accuracy of prediction

Accurate prediction of solar radiation is necessary for efforts at solar energy development as an electrical energy source over a long-term period. Predictions of solar radiation by local weather forecasting are almost coincident with the surface observation results reported by JMA (Figures 3-6). The average of hourly, monthly, and annual solar radiation predictions generally shows good agreement with observation results. The most accurate result is the annual average over four years, for which there are almost no visible differences from January through December. Local weather forecasting has provided good accuracy by evaluating as long an average period as possible. Therefore, even if no observation exists, then the database is useful for predicting solar radiation in the future for developing solar power generation facilities in view of the long-term average.

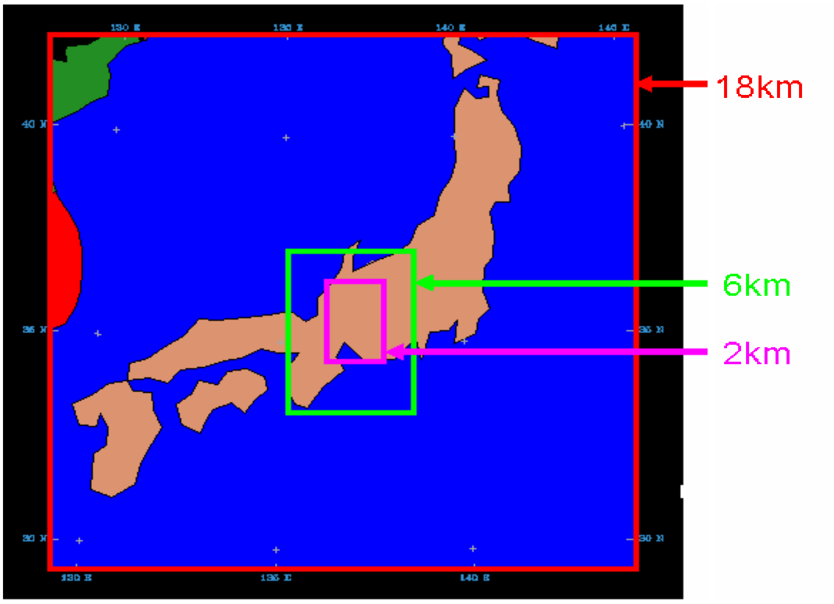


Figure 1. Computational domains of MM5

Table 1. Computational settings of MM5

	Domain 1	Domain 2	Domain 3
Horizontal resolution	18 km	6 km	2 km
Number of vertical layers	20 [from surface (1000 hPa) to top (100 hPa)]		
Time step	54 s	18 s	6 s
Forecast time	48 hr (including a lead time of 12 hr)		
Initial and boundary condition	JMA GANAL (time interval: 3 hr, 20 km grid)		
Sea surface temperature data	NCEP daily SST （1°×1°grid)		
Cloud physics scheme	Reisner graupel [19]		
Cumulus parameterization	Kain–Fritsch [20]	none	none
Boundary layer scheme	Eta [21]		
Radiation scheme	Cloud radiation [22]		
Surface scheme	Five-layer soil [23]		

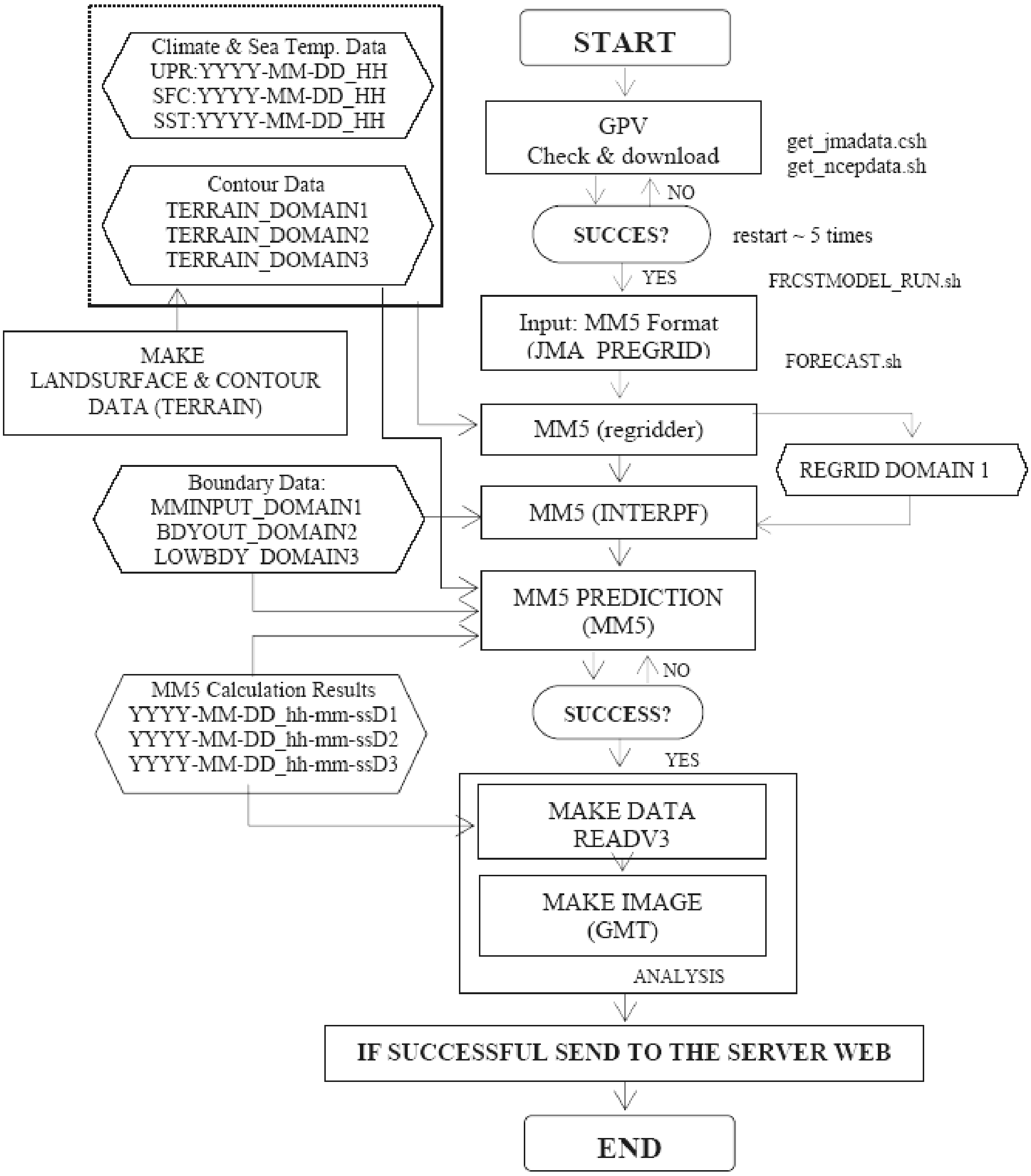


Figure 2. Schematic flow of the local weather forecast by Gifu University.

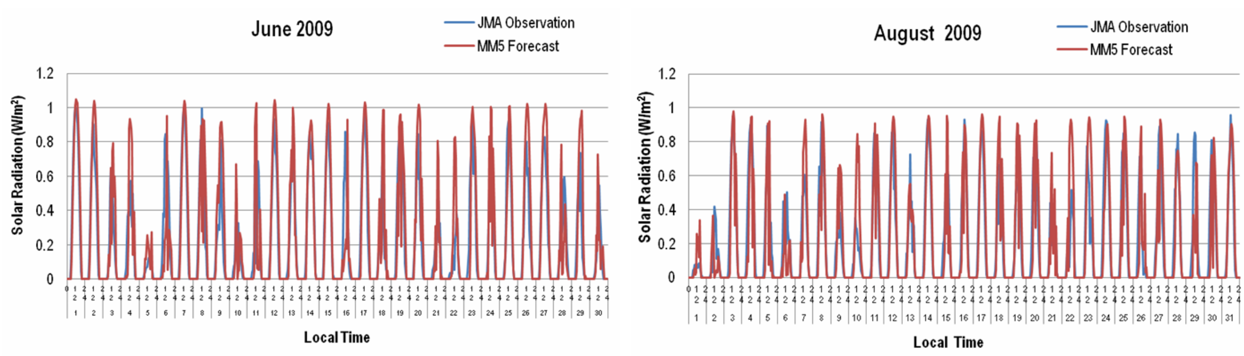


Figure 3. Comparison of time series of hourly solar radiation between JMA observation and MM5 forecast at Gifu City in June and August 2009

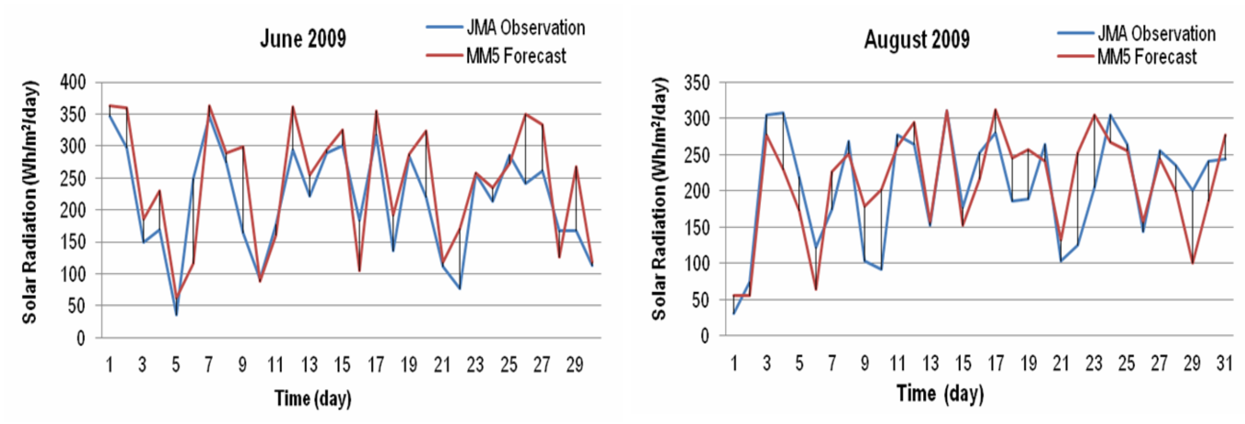


Figure 4. Comparison of time series of daily averged solar radiation between JMA observation and MM5 forecast at Gifu City in June and August 2009

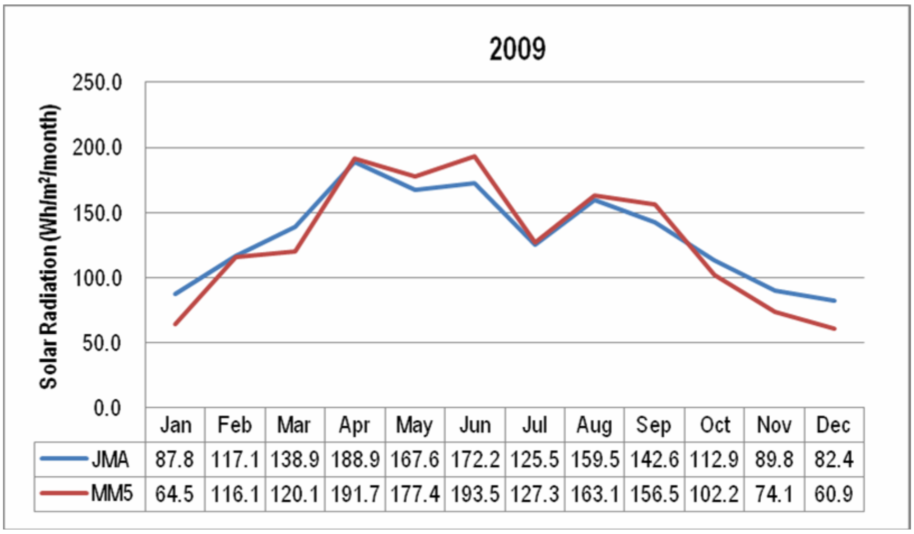


Figure 5. Monthly averaged solar radiation in 2009 at Gifu City

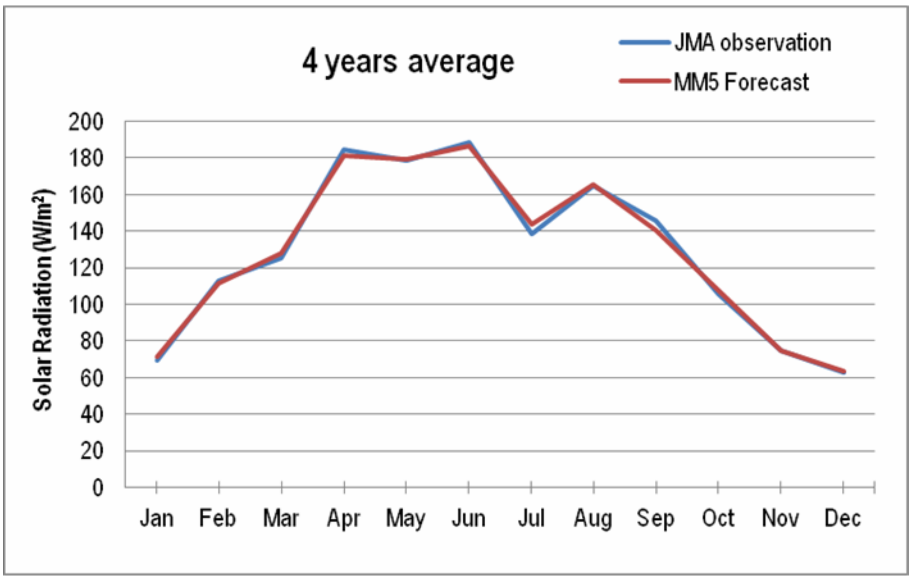


Figure 6. Solar radiation averaged for each month for 2006–2009 in Gifu City

Figure 3 presents a comparison of time series of hourly solar radiation pattern between predictions by the MM5 forecast and observations results by JMA in June and August in 2009. Results show that the production of solar radiation was favorable, with maximum production of greater than 0.8 kW/m^2 at noon and only a few days in each month lower than that figure. Figure 4 presents a comparison of time series of the daily averaged solar radiation between predictions and observations in June and August 2009. It shows that differences in both exist between predictions and observations. Solar radiation fluctuates daily to some degree, which means that the diurnal data are less effective to use as a database for estimating the availability of solar radiation because of its uncertainty and variability in hourly time series of the solar radiation. However, the monthly and annual averaged database appears to yield a good prediction of solar radiation production. Therefore, it is useful for long-term estimation of solar radiation availability.

3. Solar power potential

Solar radiation is affected mainly by topography, sun altitude, clouds, and surface conditions. Therefore, spatial distribution of 2 km mesh, which can resolve the high-resolution structure of these effects, is necessary for estimating the solar radiation abundance. Figure 7 presents the horizontal distribution of the terrain elevation height for a 2 km mesh covering Aichi and Gifu Prefectures. Northern Gifu is dominated by highland areas (green and blue) including Takayama and Kawai areas. Southern Gifu and Aichi are lowland regions (purple) including Nagoya and surrounding areas. Generally, the climate conditions in the northern area differ vastly from those in the southern area. The northern area is strongly influenced by weather systems induced by the Sea of Japan and localized high mountains, whereas the southern area is affected by climate conditions originating from the Pacific Ocean.

Figure 8 shows the spatial distribution of yearly averaged solar radiation during 2006-2009. The figure portrays marked variation from year to year in that the averaged solar radiation is high in both 2007 and 2008, but not in 2006 and 2009. The distribution of solar radiation varies in each place, especially depending on the altitude. Generally, solar radiation in the highland areas is greater than that in lowland areas. Based on the distribution of the yearly averaged solar radiation in 2006, almost no difference distribution of solar radiation is visible between southern and northern areas. The most remarkable difference is apparent in the distributions in 2007 and 2008. These variations might result from year-by-year climate variability. The main common feature is that diurnal solar radiation in the northern area is greater than that in the southern area, except for steeply sloping mountain areas facing the Sea of Japan. These results indicate that the yearly averaged solar radiation changes in time and space. Therefore the local weather forecasting database, which is continuous in time and space, is extremely useful for estimating the accumulated solar energy in Gifu and Aichi Prefectures.

Figure 9 presents fluctuations of solar radiation monthly averaged over four years at the following eight representative points: Nagoya, Toyota, and Gifu, which are located in the lowland area below 100 m altitude in the southern area, Takayama, Gero, Kawai, and Miboro, which are located in mountain areas in the northern area, and Hachiman, which is located between low and high regions. Solar radiation peaks during April-June with the maximum production at Takayama and Kawai of more than 250 W/m^2 and the minimum at Nagoya of around 200 W/m^2. Solar radiation in winter decreases drastically until it reaches half of its production in summer. In addition, the incoming solar radiation at Takayama and Kawai is lower than that in the southern area because sunny days are fewer in winter as a result of the influence of the climate affected by the Sea of Japan. These conditions are dependent on the effects of localized weather systems in both regions.

In winter, temperatures in the northern area are lower than those in the southern area around Nagoya. Consequently, the frequency of snowfall in the northern area around Takayama is greater and longer than that in the southern area. Therefore, solar radiation around Takayama decreases dramatically compared to that around Nagoya during the winter. The result in summer is completely the opposite of that in winter: the monthly averaged solar radiation around Takayama is greater than that in and around Nagoya. Those conditions are attributable to the differences of complex terrain and local weather conditions in the respective regions.

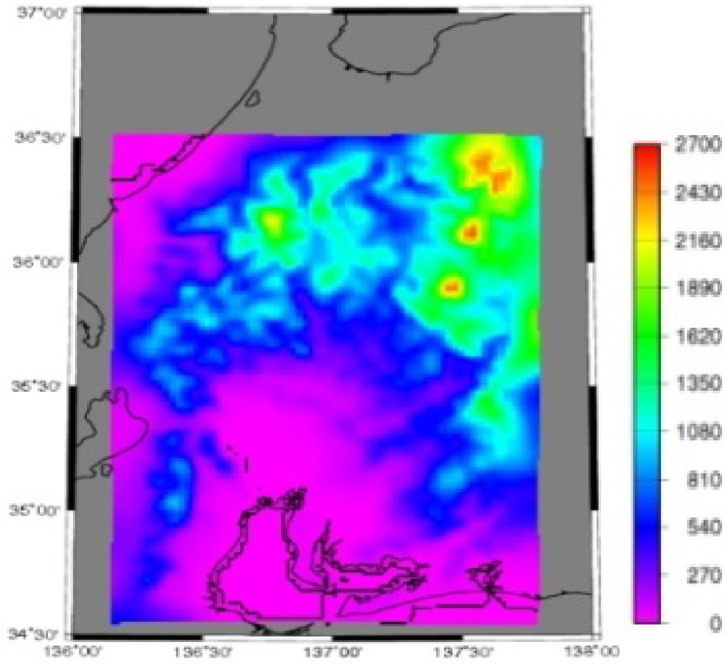
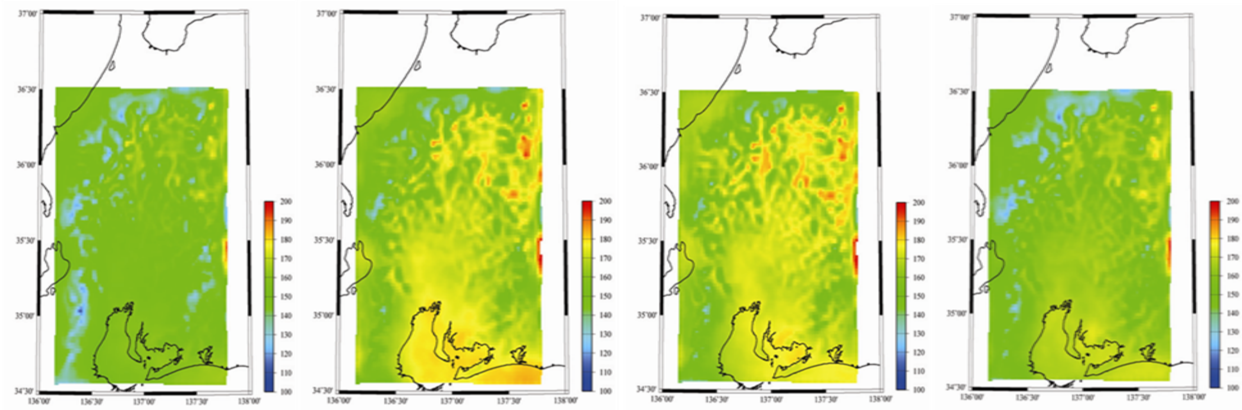


Figure 7. Horizontal distribution of the terrain elevation height



2006 2007 2008 2009

Figure 8. Yearly average of solar radiation during 2006-2009

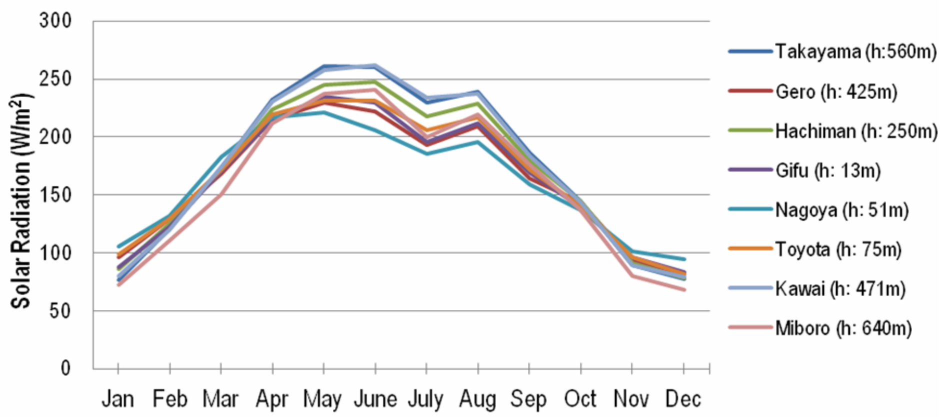


Figure 9. Monthly average of solar radiation over four years at representative points

Based on a time series of the annual average of solar radiation (Figure 10), incoming solar radiation on an annual average basis in Takayama is greater than that in Nagoya, which indicates that the northern–southern difference of winter climate only slightly affects the annual average of solar radiation at all. In other words, solar radiation during the year in each region is almost entirely determined by summer climates during March–September.

Day-to-day weather pattern changes have a considerable influence on the daily average of solar radiation but no significant effect on the annual average. The effects of winter climate are slight for the annual average over four years because the sunny days during the year are more numerous than the cloudy days, so that the effects of sunny days are more dominant than the effects of cloudy days during the year. These conditions are apparent in the region of Takayama and Kawai, which is located in the highland and near the Sea of Japan. They have a minimum amount of solar radiation: around 170 W/m^2. Their amounts are approximately 20 W/m^2 higher than those in the Nagoya area (Figure 10). The difference of solar radiation between Takayama and Gero is large because of the difference of local climate conditions in both regions. In Gero, a dam and lake cause high evaporation to the atmosphere, so that the content of water particles in the air is greater. Consequently, the amount of solar radiation in Gero is somewhat lower.

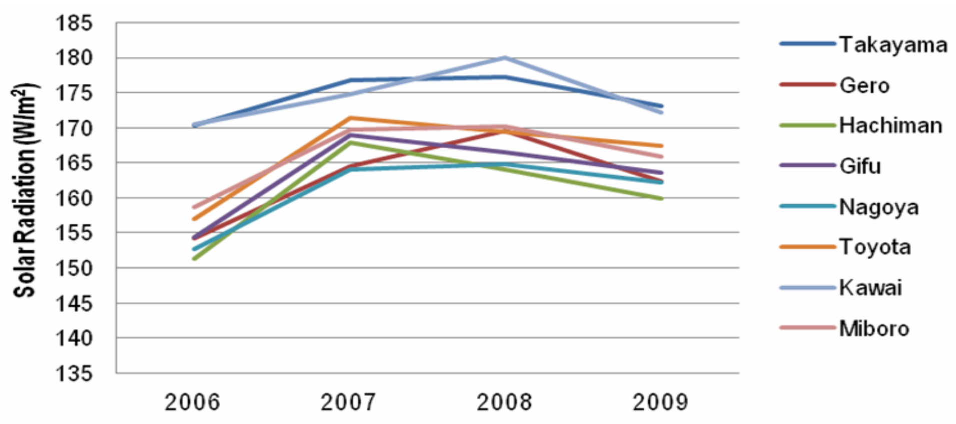


Figure 10. Annual average of solar radiation at representative points during 2006-2009

Table 2 presents monthly production of solar radiation in Gifu. It shows that the monthly production of solar radiation was greater than 100 Wh/m^2/month during the four years of 2006–2009. The annual average of solar radiation production was about 1,553 Wh/m^2/year, which means that Gifu has favorably sufficient solar energy resources.

Table 3 shows the monthly electric power generation observed from a solar cell on the roof of the Gifu University library building during February–September in 2010. The panel area is 261 m^2; its rated output is 40.8 kW. Its greatest power generated was about 6,102 kWh in May. The average annual of electric energy production is around 4,741 kWh/month, which indicates that the utilization of solar cells integrated in the building is sufficiently good. It should be developed continuously.

Figure 11 presents a comparison of observed and predicted hourly solar power generation during 10 days in June and September 2010. Overall, predictive values well reflect the true amount of electricity production except for day 7, which was overestimated by about 20 kWh. Electricity production is quite stable during 10 days in June. The highest production was greater than 30 kWh at the sunny noon. In contrast, the cloudy noon periods on 7 and 8 June show production of no more than 10 kWh. In September, the predictive value coincides with the observed electricity production. The highest value is generally greater than 25 kWh, except for some overcast days: 6 and 8 September.

Figure 12 portrays the time series of hourly solar radiation with electrical energy production in July and August 2010. The highest production occurs at noon, reaching over 700 W/m^2. Electrical energy production shows similar temporal change with the solar radiation production, which means that the electrical energy is reproduced sufficiently well to supply the energy demand with average production of 4,741 kWh/month in 2010. Therefore, using the database of the local weather forecasting, it is readily apparent that we can estimate the power output from the amount of solar radiation easily, and with high accuracy.

Table 2. Monthly average solar radiation in Gifu City (Units: $Wh/m^2/month$)

Month	2006	2007	2008	2009	Total	Average
1	75.59	78.86	79.76	64.52	295.72	73.93
2	103.18	121.04	299.62	116.08	439.93	109.98
3	126.35	134.42	142.48	120.08	523.34	130.83
4	154.64	187.98	175.94	191.68	710.24	177.56
5	153.24	206.11	181.02	177.43	717.80	179.45
6	187.98	187.98	165.75	193.53	735.24	183.81
7	138.90	146.07	183.71	127.25	595.93	148.98
8	168.47	179.23	152.34	163.10	663.14	165.78
9	117.60	126.86	138.90	156.49	539.86	134.96
10	112.02	116.50	106.64	102.16	437.31	109.33
11	76.86	78.71	69.45	74.08	299.10	74.77
12	61.83	53.77	81.55	60.94	258.09	64.52
Total	1,473.66	1,617.52	1,577.16	1,547.35	6,215.69	1,553.92

Table 3. Monthly accumulated power generated observed at Gifu University in 2010

Month	Actual monthly amount of power generated (kWh)	Capacity Utilization (%)	Average diurnal solar radiation (W/m^2)	Conversion efficiency (amount of electricity/ solar radiation)
2	2,812	10	104.7	0.15
3	4,420	15	145.5	0.16
4	4,800	18	191.9	0.13
5	6,102	20	247.7	0.13
6	5,017	17	233.1	0.11
7	5,064	17	215.9	0.12
8	5,305	17	226.4	0.12
9	4,410	15	169.0	0.14

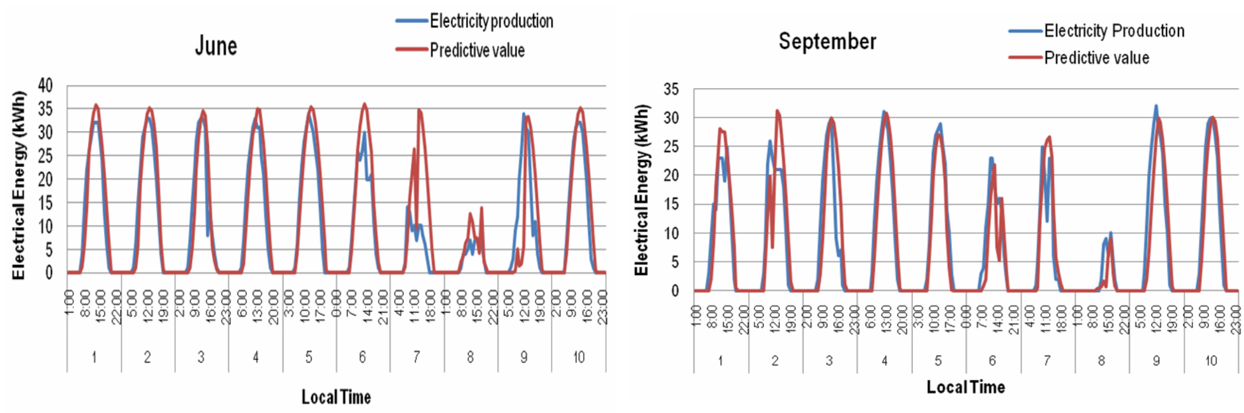


Figure 11. Comparison of time series of hourly solar power generation during 1-10 June and 1-10 September, 2010

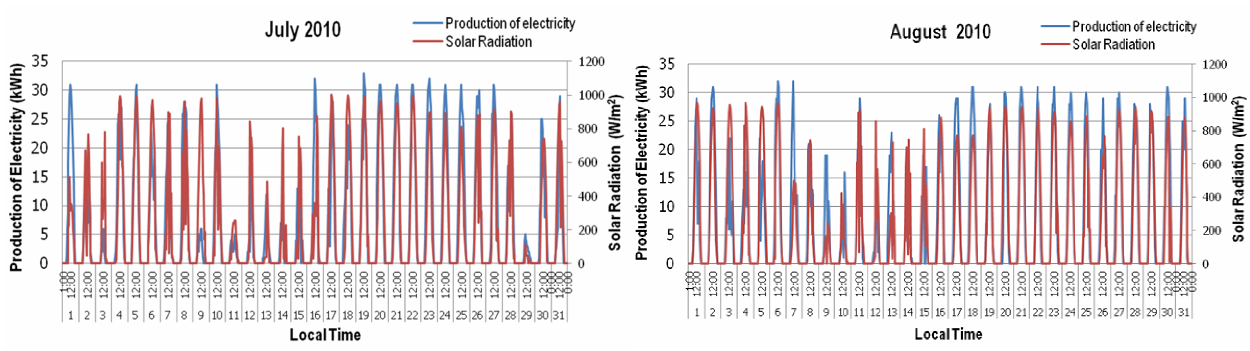


Figure 12. Comparison of time series of hourly solar radiation with electricity production in July and August 2010

4. Variation of solar radiation

Solar radiation is influenced by the sun's altitude and cloud conditions. Figure 13 presents diurnal fluctuations of solar radiation at Gifu in June and December 2009. Results show that the amount of solar radiation in December is less than that in June. Effects of cloud-cover vary considerably every day during the month, sometimes causing a significant amount of rainfall (up to 1,700 mm/year), correspondingly reducing the diurnal solar radiation. Figure 14(a) shows that the daily averaged solar radiation fluctuates during June 2009 to a great degree in every location. This result reflects that the effect of cloud cover on the daily average influences on the solar radiation in all locations in Gifu and Aichi Prefectures. Solar radiation fluctuation during June averaged over four years (Figure 14b) is less than that during June 2009, but it remains visible in each location. Consequently, the assessment of cloud conditions using our high-resolution database is needed for the development of solar power plants with high efficiency.

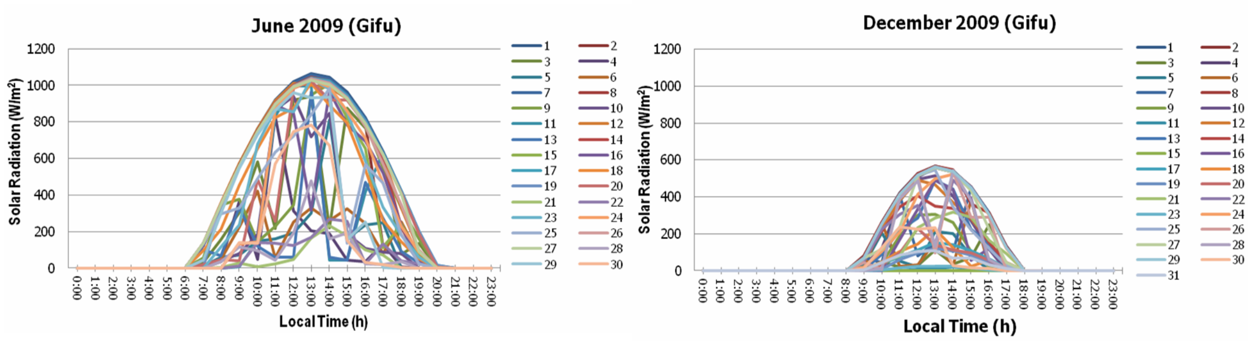
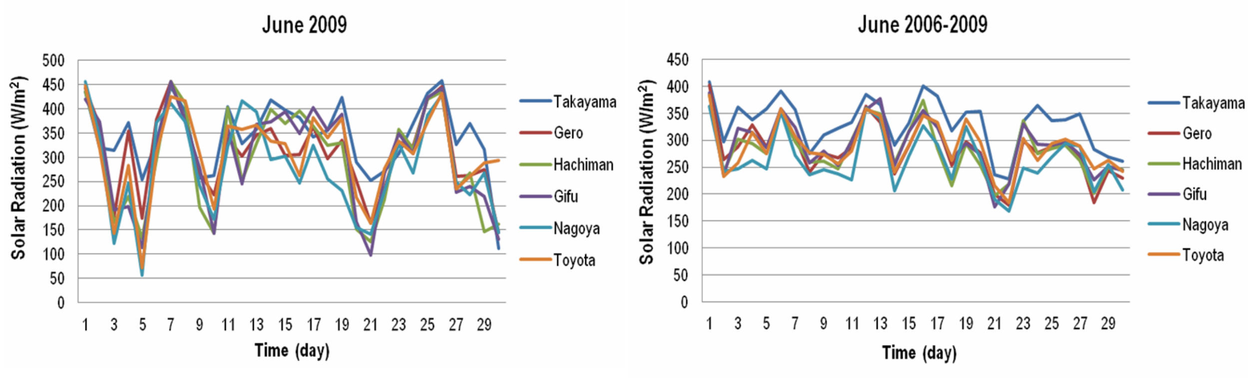


Figure 13. Diurnal fluctuations of solar radiation at Gifu in June and December 2009



(a) (b)

Figure 14. Fluctuations of daily averaged solar radiation in the representative points: (a) in June 2009; (b) in June averaged for 2006-2010

Figure 15 presents the time series of diurnal solar radiation averaged in each month 2009 at Gifu and Nagoya. Results show that no fluctuation occurred during the daytime in each month. The diurnal fluctuations presented in Figure 13 can be removed by monthly averaging. Solar radiation increases gradually from early morning until noon. Subsequently, it decreases gradually until late afternoon. Consequently, random cloud effects can be eliminated through monthly averaging. Figure 16 depicts the time series of monthly averaged solar radiation in June and December at four representative points. The data show that the curve of averaged solar radiation is similar in each location. Solar radiation in December decreases to half of its amount in June. In summer, solar radiation is the highest in Takayama and the lowest in Nagoya. In contrast to results in winter, a reverse trend is apparent in summer, which indicates that local climate conditions can influence differences of solar radiation abundance between the north and south. Based on temporal distributions in Figures 15 and 16, the standard curve can be estimated for any geographic point and any time for the modeling domain and period. Such an obtained standard curve enables the evaluation of the imbalance between supply and demand of electricity at any time.

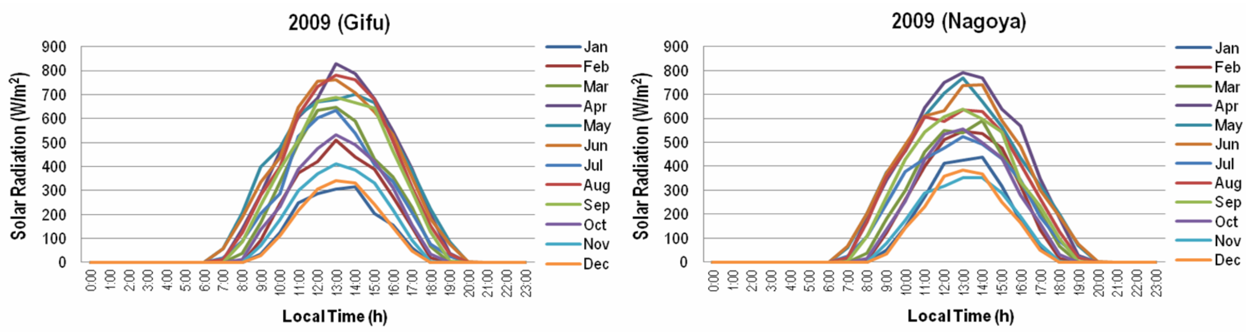


Figure 15. Time series of diurnal solar radiation averaged monthly in 2009 in Gifu and Nagoya

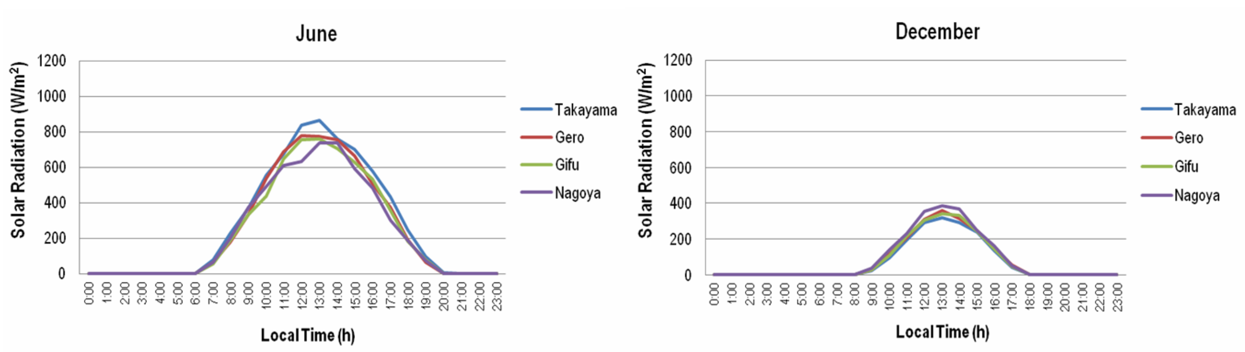


Figure 16. Time series of diurnal solar radiation averaged in June and December at representative points

Figure 17 portrays the fluctuations of diurnal solar radiation averaged on 4 and 6 June 2009, averaged over each circumference of a given radius: 0 km (1-point), 8 km, 16 km, 24 km, 32 km, 60 km and 100 km, centered at Gifu. Results show that the fluctuations of solar radiation differ in response to the horizontal averaging area. For the 8 km radius averaging area, solar radiation fluctuations are considerable during the daytime. However, for the 100 km radius averaging area, the solar radiation fluctuations are small, except for the case of 6 June, when a synoptic-scale cyclone passed through the Japan archipelago, which indicates that a larger averaging area smoothes the fluctuations of solar radiation more strongly.

Figure 18 displays the fluctuations of diurnal solar radiation averaged over 8 km and 100 km radius areas centered on Gifu during the first week of June. Production of solar radiation during the week varies to a great degree. The highest production during a sunny day is observed at noon. The maximum solar radiation is over 1000 W/m^2, which means almost up to 800 W/m^2. Distributions of the maximum and mean of solar radiation are similar in both cases of the 8 km and 100 km radius averaging area whereas there are no fluctuations during day time. Fluctuations of diurnal solar radiation are greater in the case of

8 km than in those in the case of a 100 km radius averaging area, but it remains visible on day 6. The effects of cloud cover on solar radiation can not necessarily be removed by spatial averaging.

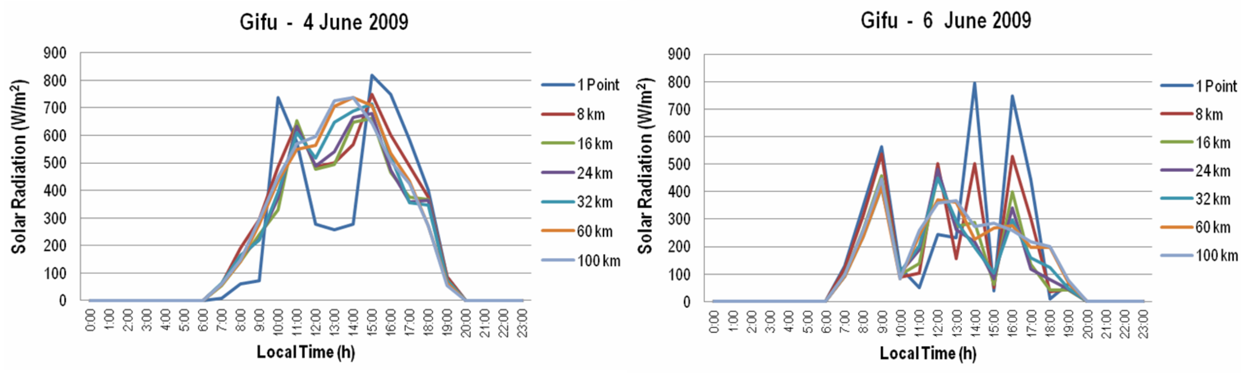


Figure 17. Fluctuations of diurnal solar radiation averaged over each circle centered at Gifu

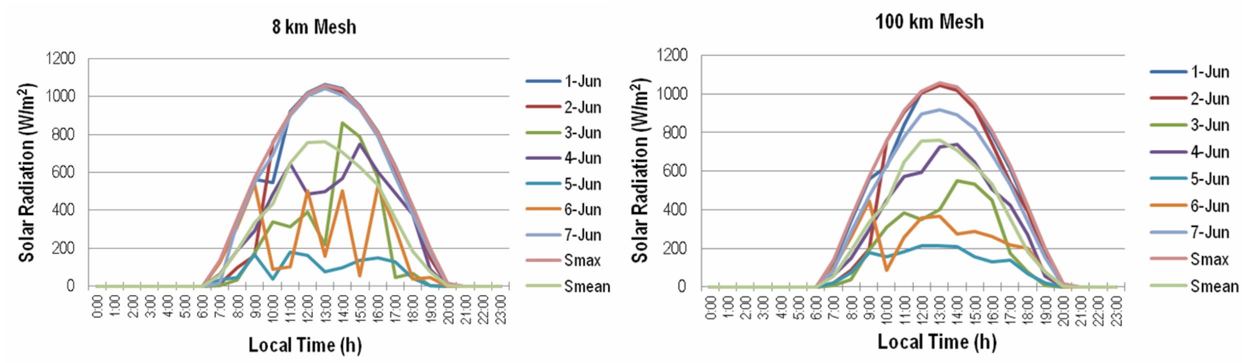


Figure 18. Fluctuations of diurnal solar radiation averaged over 8 km and 100 km radius centered at Gifu

Clouds aloft can strongly influence the amount of solar radiation at the surface. Effects of cloud cover on solar radiation can not necessarily be removed by spatial averaging, but the effects tend to decrease with a larger averaging area. The fluctuations of solar radiation are quite great in the case of the 8 km radius averaging area compared to those of the 100 km radius averaging area (Figures 17 and 18). The temporal distribution shows that effects of clouds vary greatly in terms of time and space, but they can be removed through monthly averaging (Figures 13 and 15). Solar radiation during a year is almost certainly dependent on sun conditions during March–September. Therefore, the balance between supply and demand of electricity can be estimated using a standard curve obtained from the temporal average (Figures 15 and 16). When the amount of solar radiation at a certain moment averaged by the 100 km radius area does not necessarily yield the standard curve, we can estimate the system of storage and auxiliary power required based on the evaluated results of imbalance between supply and demand.

5. Conclusion

Predictions of solar radiation by local weather forecasting are similar with observation results obtained by JMA, which means that local weather forecasting has high accuracy. Therefore, the data base are useful for predicting solar radiation in the future. Solar radiation abundance varies among locations depending on the altitude, climate, and weather conditions. Solar radiation during the year in each region is almost certainly determined by sun conditions during March–September. Electrical energy generated by photovoltaic cells is almost directly proportional to the solar radiation amount. Its peak is in May at 6,102 kWh/month, indicating that solar energy can be generated favorably at Gifu.

Effects of clouds on solar radiation vary by time and space during each month. The effects can not necessarily be removed by spatial averaging, but they are decreased over larger averaging areas. Effects of cloud cover are greater in cases of the 8 km radius averaging area than for a 100 km radius averaging area. However, temporal distribution shows that the effects of clouds can be removed by monthly averaging. Consequently, the balance between supply and demand of electricity can be estimated using a standard curve obtained from the temporal average. When the amount of solar radiation at a certain moment averaged by the 100 km radius area does not necessarily yield a standard curve, we can estimate the systems of storage and auxiliary power that are necessary based on evaluated results of an imbalance between supply and demand.

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