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OPTIMAL MIX OF SOLAR AND WIND POWER FOR ELECTRICITY SUPPLY MATCHING WITH DEMAND

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SUMMARY: This paper reports the optimal ratio of electricity generation from solar photovoltaic and wind power corresponding to electricity demand in Japan. The monthly electricity demand in 1999-2012 and the electricity generation of Extended AMEDAS weather data are used in order to minimize the mismatching of demand-supply equations. The results of correlation analysis show the optimal ratio of solar/wind is between 64/36 to 49/51. However the results depend on the differences of electricity demands in summer and winter.

Keywords: photovoltaic, wind power, correlation analysis, optimal mix

INTRODUCTION

The domestic renewable energy sources have a great attention from the view point of safety, security, energy independence and no carbon emission. The electricity generations by solar and wind power are intermittent and fluctuating because of weather conditions.

It is necessary to analyze the demand-supply to decrease mismatching caused by solar and wind power when they are dominated. We simulated renewable electricity generations by hourly weather data and analyzed the demand-supply mismatching during 1999-2012 to find the optimal mix ratio of solar and wind power.

WEATHER DATA

In order to calculate solar and wind power, we used the annual weather data of Extended AMEDAS for 2000, which has the hourly data of solar radiation and wind speed at 842 sites nationwide of Japan. [1]

ELECTRICITY DEMAND

The electricity demand of ten electricity companies is shown in Fig.1.[2] There is much decline in 2009 because of economic recession, and there were declines in 2011 and 2012 because of Fukushima Daiichi Nuclear power accident caused by earthquake of Magnitude 9 in East Japan in March 11, 2011.

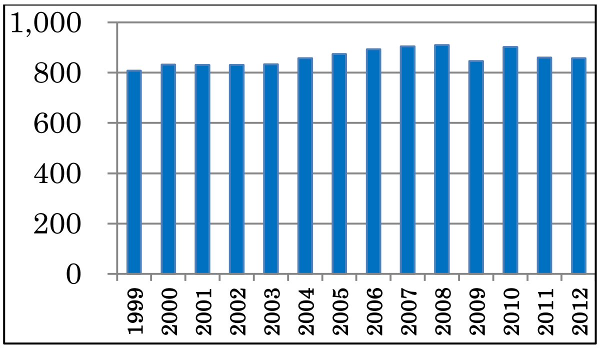

Fig.1 Electricity demand in 1999-2012 (TWh)

There are electricity grids among nine electricity supply companies, but the electricity grid of Okinawa area, the most southern area, is remote and not connected with the grid to other power companies, so we do not treat the electricity supply of Okinawa area in this study. The mutual connection grid lines among the nine power grids are not so large. We treated the nine areas as an integrated single grid in this study ignoring the present capacity of mutual grid.

SOLAR POWER

The hourly electricity generation from solar panel is calculated using horizontal solar radiation data at 842 sites in Japan. The calculation method is to split horizontal radiation into direct beam and scattered irradiance and to combine the both solar lights on the panel oriented at south with tilt angle. The optimum tilt angle is set at “latitude -5” degree at each construction site as is known experimentally. The inverter of 94% efficiency is included with partial load factor curve.

WIND POWER

Unit of 2MW wind machine with three blades and horizontal axis is used to calculate the wind power in respective sites. The blades start to rotate at cut-in wind speed 3m/s, and stop at cut-out wind speed 25m/s. The conversion efficiency is assumed 40%. The diameter of rotor is 80m and hub height is 56m. Wind speed of meteorological data is extended by power factor law to calculate the wind speed at hub height. We excluded the wind power sites having capacity factor less than 18%, and finally 99 sites are selected for wind sites among 842 data sites.

SCALE OF SOLAR AND WIND

At first the hourly generation amount by single unit of 100kW solar system and 2MW wind machine for respective site are calculated.

The necessary unit numbers of solar 100kW are calculated as proportional to annual electricity demand of respective regions. The allocations of 2MW wind machines for each region are assumed based on the wind energy potential study.[3] These unit numbers of solar and wind machines are multiplied with hourly generation to calculate electricity supply throughout a year. The site selection of wind power resulted in the average capacity factor 27%. The average capacity factor of solar power is approximately 12%. [4][5]

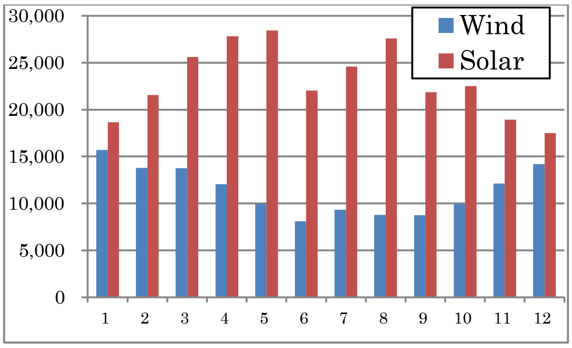

Fig.2 Monthly solar and wind (GWh)

Monthly solar and wind generations with annual solar/wind ratio=2 throughout year are shown in Fig2. Solar and wind are mutually complementary. Wind is low in summer and high in winter, but solar is reverse.

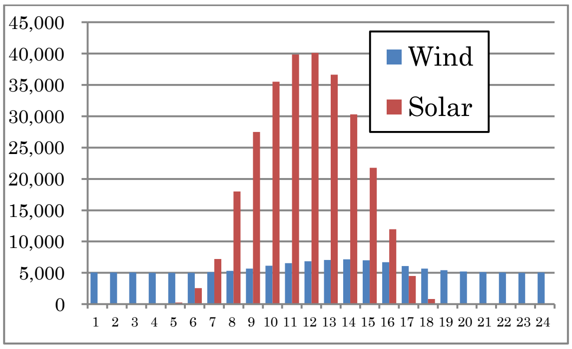

Fig.3 Hourly solar and wind(GWh)

Fig. 3 shows hourly generations with annual solar/wind ratio=2 throughout year. Hourly wind is flat for 24 hours and hourly solar has bell shape pattern for daytime.

MISMATCHING EQUATION

There are studies on the fully renewable supply by combination of solar and wind power using data of electricity load and weather in Europe. [6], [7] They showed the statistical analysis that the optimal mix of solar and wind can be found by using monthly data. We also tried similar study using Japanese data.[8] They defined D(t), the mismatch equation of load and supply as follows,

$$D(t)= a*S(t)/[S]+b*W(t)/[W]+–L(t)/[L] \qquad (1)$$

Where W(t) and S(t) present total generations of wind and solar for month t. [W] and [S] are monthly average generations of wind and solar during certain periods. L(t) is electricity load for month t.

The coefficients a=[S]/[L], b=[W]/[L] show the fraction of respective power supply divided by average load [L]. The coefficients have relation a+b=1.

CRRELATION ANALYSIS of HOURLY GENERATION

We tried to analyze relationship between the renewable electricity and the demand by correlation analysis. When 'b' is excluded with equation b=1–a and the variables are expressed in normalized form, substituting S(t)/[S] with S(t), W(t)/[W] with W(t) and L(t)/[L] with L(t), the equation (1) can be written as,

$$L(t)–W(t)=a*(S(t)–W(t))–D(t) \qquad (2)$$

Figure 4 shows normalized monthly electricity load, solar and wind power for 1999-2012.

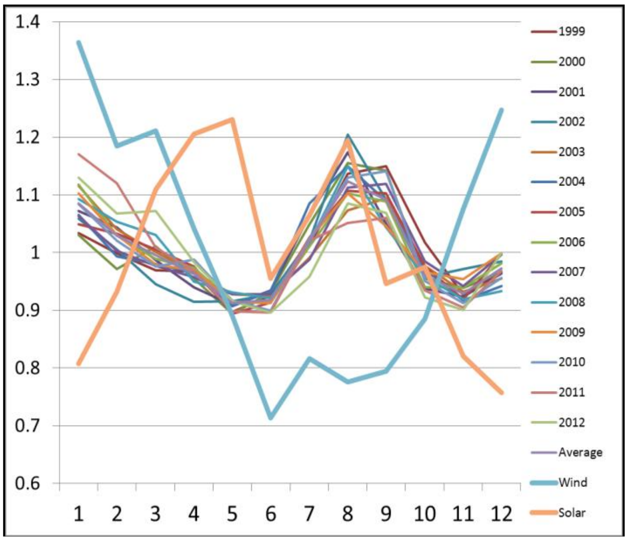

Fig.4 Normalized monthly solar, wind and electricity load for 1999-2012. Wind and solar are shown in bold lines.

Table 1 shows S(t), W(t) and the energy demand L(t) in 1999-2006. Table 2 shows that for 2007-2012. Average shows for 1999-2012.

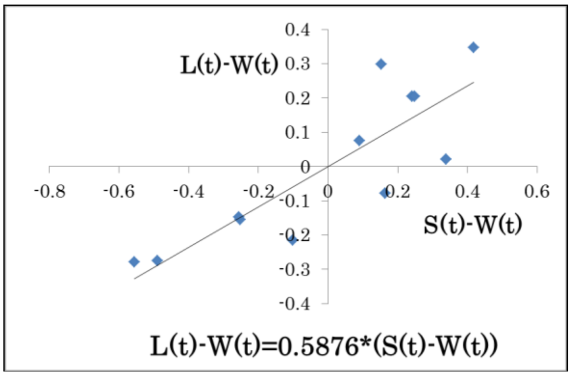

Fig.5 Correlation diagram of S(t)-W(t) and L(t)-W(t).

In the equation (2), we expect to find 'a' to minimize the mismatch D(t). So we tried the correlation analysis of L(t)-W(t) and S(t)-W(t). The relationship between the variables for average case is,

$$L(t)–W(t)=0.588*(S(t)–W(t)) \qquad (3)$$

This result shows that the optimal mix to minimize mismatch is at a=0.588, Fig.5 shows the scattering diagram of L(t)-W(t) and S(t)-W(t) for 12 months for average load data in 1999-2012 with the regression line of equation (3).

The correlation line L(t)-W(t)=0.588*(S(t)-W(t)) shows the least square regression. The line shows a=0.5876 which means almost 60% solar share is the optimal mix.

The solar ratio 'a' for respective year is calculated by correlation analysis of equation (3) during 1999 -2012. They are shown in Table 1 and 2. The estimates of solar ratio 'a' are shown in the bottom lines of the tables.

Table 1 Monthly L(t)-W(t) in1999-2006

	L(t)-W(t)	L(t)-W(t)	L(t)-W(t)	L(t)-W(t)	L(t)-W(t)	L(t)-W(t)	L(t)-W(t)	L(t)-W(t)
Month	1999	2000	2001	2002	2003	2004	2005	2006
1	−0.330	−0.333	−0.291	−0.305	−0.248	−0.298	−0.315	−0.246
2	−0.186	−0.213	−0.141	−0.179	−0.144	−0.191	−0.151	−0.155
3	−0.241	−0.200	−0.224	−0.265	−0.209	−0.230	−0.205	−0.222
4	−0.074	−0.086	−0.101	−0.127	−0.075	−0.076	−0.065	−0.068
5	0.006	0.003	0.018	0.025	0.036	0.016	0.003	0.023
6	0.212	0.218	0.221	0.215	0.211	0.219	0.200	0.200
7	0.196	0.233	0.248	0.205	0.176	0.269	0.211	0.195
8	0.360	0.378	0.397	0.429	0.297	0.373	0.331	0.326
9	0.355	0.347	0.256	0.298	0.299	0.295	0.308	0.294
10	0.132	0.070	0.052	0.072	0.092	0.087	0.090	0.054
11	−0.150	−0.137	−0.152	−0.104	−0.143	−0.159	−0.157	−0.136
12	−0.281	−0.281	−0.283	−0.263	−0.291	−0.304	−0.249	−0.265
a=	0.637	0.645	0.616	0.621	0.560	0.647	0.588	0.555

Table 2 Monthly S(t)-W(t) and L(t)-W(t) in 2007-2012

	S(t)-W(t)	L(t)-W(t)	L(t)-W(t)	L(t)-W(t)	L(t)-W(t)	L(t)-W(t)	L(t)-W(t)	L(t)-W(t)
Month	AMEDAS	2007	2008	2009	2010	2011	2012	Average
1	−0.556	−0.300	−0.270	−0.261	−0.280	−0.193	−0.234	−0.279
2	−0.252	−0.181	−0.131	−0.154	−0.163	−0.064	−0.116	−0.155
3	−0.102	−0.234	−0.180	−0.231	−0.235	−0.202	−0.139	−0.215
4	0.164	−0.084	−0.092	−0.072	−0.054	−0.073	−0.058	−0.079
5	0.340	0.037	0.040	0.024	0.026	0.007	0.025	0.021
6	0.241	0.214	0.208	0.199	0.186	0.182	0.182	0.205
7	0.248	0.172	0.202	0.209	0.208	0.204	0.142	0.205
8	0.419	0.336	0.373	0.326	0.354	0.275	0.309	0.347
9	0.152	0.325	0.249	0.251	0.346	0.265	0.274	0.297
10	0.090	0.099	0.073	0.080	0.065	0.049	0.037	0.075
11	−0.255	−0.133	−0.157	−0.122	−0.164	−0.171	−0.176	−0.147
12	−0.489	−0.250	−0.314	−0.248	−0.290	−0.279	−0.246	−0.275
	a=	0.592	0.601	0.551	0.612	0.492	0.512	0.588

(The average is during 1999-2012)

Table 2 includes S(t)-W(t) and the average of L(t)-W(t). The results show that the change of solar ratios depends on the differences of summer and winter electricity demand. As the electricity demand in winter is getting larger as seen in the latest years, the ratio of wind power becomes larger.

The changes of solar share are shown in Fig.6. It shows that the solar ratio decreased in 2011 and 2012. It is because of the decline of electricity demand in summer and increase in winter.

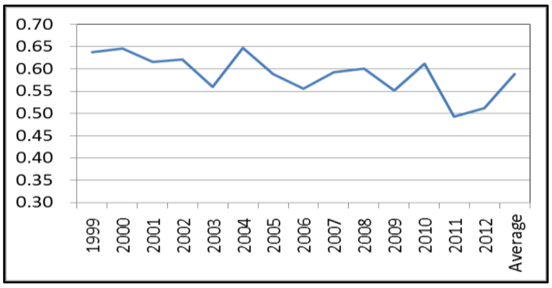

Fig.6 Solar ratio 'a' during 1999-2012 and average

The average of solar ratio 'a' is 0.588 during 1999 and 2012. But it is 0.647 in 2004 and 0.492 in 2012.

The differences are caused by the relative increase of electricity demand in winter and the decrease in summer. If the electricity demand of winter is large, then the ratio of wind power becomes large correspondingly.

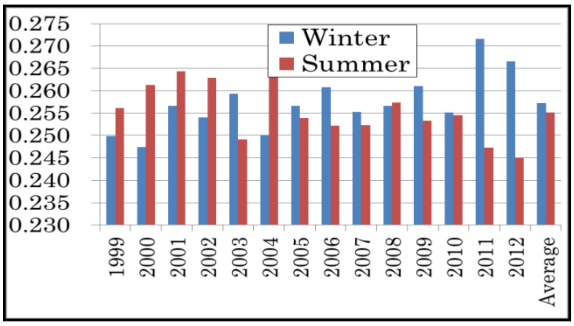

Fig.7 Share of electricity demand in summer and winter

Fig.7 shows the electricity demand share in summer (June, July and August) and winter (December, January and February). They are basically around 0.25 for 3 months in 12 months a year. The average is nearly 0.255 in Fig.7.

The long term trend is the decrease of summer demand and increase of winter demand as shown in Fig.7. The electricity demand in summer has decreased mainly by the efficiency improvement of coolers and the winter demand increased by introductions of heat pump for room heating during 1999 and 2007 as a long term trend. The decrease of electricity demand in summer after 2011 is affected mainly by people's behaviors of energy saving because of supply constraints publicly announced. The analysis showed that the solar ratio is sensitive to seasonal electricity demand pattern.

CONCLUSION

Using electricity demand and weather data at 842 sites in Japan, we tried dynamic simulation of annual electricity supply from solar and wind power to find the optimal mix ratio of solar and wind powers. The results of correlation analysis show optimal mix of solar/wind to minimize mismatch of demand and supply is between 64/36 to 49/51. The analysis showed the solar/wind ratio depends on the electricity demand in summer and winter

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