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PV AND WIND POWER – COMPLEMENTARY TECHNOLOGIES

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ABSTRACT

PV and wind power are the major renewable power technologies in most regions on earth. Depending on the interaction of solar and wind resources, PV and wind power industry will become competitors or allies. Time resolved geospatial data of global horizontal irradiation and wind speeds are used to simulate the power feed-in of PV and wind power plants assumed to be installed on an equally rated power basis in every region of a 1°x1° mesh of latitude and longitude between 65°N and 65°S. An overlap of PV and wind power full load hours is defined as measure for the complementarity of both technologies and identified as ranging between 5% and 25% of total PV and wind power feed-in. Critical overlap full load hours are introduced as a measure for energy losses that would appear if the grid was dimensioned only for one power plant of PV or wind. In result, they do not exceed 9% of total feed-in but are mainly around 3% - 4%. Thus the two major renewable power technologies must be characterized by complementing each other.

Keywords

Photovoltaics, Wind power, Resource Assessment, Energy Options

1 INTRODUCTION

Sun and wind are among those energy resources which will hardly ever cease and which are available both in abundant amounts and for free all over the world. The markets of photovoltaic (PV) and wind energy are continuously growing at a fast pace, however most of the renewable potential still remains untapped with regards to a possible use in respective power plants and systems. For that reason and considering limited grid capacities, the degree of competition between these two energy technologies is not yet conceivable. In order to assess if PV and wind power technology and respective industries are competitors at all, an analysis of the extent to which wind and PV power plants feed-in simultaneously has to be conducted. PV and wind power are both fluctuating energy conversion technologies, however low competition in time resolved feed-in would indicate a tendency for mutual balancing effects since energy harvest would be anti-correlated. As a consequence this would reduce residual load requirements. The purpose of this work is to understand the competitive or complementary characteristics of the two major renewable power technologies. This work is part of a more comprehensive view on the economics of hybrid PV power plants.[1]

2 SOLAR AND WIND RESOURCE AVAILABI-LITY

The total and global primary energy demand has been about 151,200 TWh_{th} in the year 2008, i.e. about 17 TW of continuous energy flow [2]. However, a substantial amount of this primary energy is wasted in inefficient energy use based on burning fuels, i.e. direct use of valuable electricity would reduce the aforementioned energy flow to about 11.5 TW provided for instance by solar PV or wind power [3].

The global energy supply potential of PV and wind power exceeds by far this energy demand of mankind. The technical energy potential of solar PV and wind is assessed differently by various authors but always by factors or orders higher than total global energy demand. In 1978 Weingart estimated the solar PV potential energy flow usable for mankind being higher than 100 TW.[4] In 2003, the German Advisory Council on Global Change derived a harvestable energy flow potential for wind power of about 90 TW and a practically unlimited potential for PV.[5] However, these numbers have been adjusted in 2011 to a technical potential of about 54 TW for wind power and about 8,900 TW for solar energy and, thus also for PV [6]. In the 2008 study ‘energy [r]evolution’ by Greenpeace the utilizable energy flow has been estimated to about 35 TW for wind power and 150 TW for PV.[7] Also in 2008, Sawin and Moomaw estimated the energy flow potential to about 145 TW for PV and about 55 TW for wind power.[8] In 2009, Lu et al. estimated the energy flow for wind power to about 80 – 150 TW.[9] In 2009 Jacobson and Delucchi derived an energy flow of 40 – 85 TW for wind and 580 TW for PV.[3] In 2011 the IPCC derived a theoretically utilizable energy flow of about 190 TW for wind power and about 120,000 TW for PV.[10] An overview on the estimations is given in Table 1. Other authors clearly pointed out that wind and solar energy will become the backbone of the global energy supply and that this could happen already before 2030.[11] The insight that establishing a solar powered society is necessary, dates back many decades and was emphasized for instance by Hubbert already in 1949.[12]

Technical Potential		referenced	PV	Wind
			[TW]	[TW]
Weingart	1978	[4]	> 100	-
WBGU	2003	[5]	infinite	90
Greenpeace	2008	[7]	150	35
Sawin and Moomaw	2008	[8]	145	55
Lu et al.	2009	[9]	-	80 - 150
Jacobson and Delucchi	2009	[3]	580	40 - 85
WBGU	2011	[6]	8900	54
IPCC SRREN	2011	[10]	120000	190
Current Global Energy Demand				
including waste of heat	[TW]	[2]	17.0	
direct energy demand	[TW]	[3]	11.5	

Table 1: Technical potential of PV and wind power versus the current gloabl energy demand.

3 METHODOLOGY

3.1 METHODOLOGY DATASET

In this work, the global potentials of wind speed and global horizontal irradiation (GHI) are illustrated. Time resolved global geospatial data covering a period of 22 years (1984 to 2005) are provided by NASA [13] composed of GHI data (Surface Meteorology and Solar Energy SSE Release 6.0 – underlying data obtained from the Surface Radiation Budget 3.0 portion of NASA's Global Energy and Water Cycle Experiment GEWEX) and wind speed data (Modern Era Retrospective-analysis for Research and Applications MERRA). These data have been prepared for energy related analyses by the German Aerospace Center. Hourly time steps for GHI are obtained using a clear sky index approach, taking into account hourly clear sky irradiance data provided by DLR.

Based on the pre-processed resource data, possible hourly power generation of PV and wind power plants has been derived, averaged for a global 1°x1° grid of latitude and longitude (within 65°S and 65°N). Ambient conditions that are relevant for the simulation of power plants are the roughness length, air density and temperatures. Roughness lengths are dependent on the orography of the landscape and obstacles on its surface such as trees or buildings. The rougher the landscape, the higher is the roughness length and the larger is the difference between wind speeds near ground to those at a higher altitude. Data of roughness lengths are based on the NASA source and like GHI and wind speed prepared and provided by DLR. The air density has been calculated from monthly global average air pressure, provided by NASA. Data for monthly global average temperatures have also been taken from NASA. Since there are temperature differences between day and night and PV feed-in is only affected by day temperatures, the average data have been recalculated to get more realistic values for daytimes. Based on conclusions of AlBusairi and Möller [14] and of Montes et al. [15] the assumption is made, that differences of day temperature to average temperature are between 4 and 10 K, dependent on the location and its proximity to water. Coasts are assumed to have lower temperature differences because of the water storing heat longer than soil and leading to a steadier climate.

3.2 MODELING OF POWER PLANTS

Two power plants of 1 GW have been simulated for every 1°x1° area within 65°S and 65°N, one of PV and one of wind power. For the wind power plant it is assumed that in future hub heights of wind power plants will typically reach about 150 m. The available wind speed data give wind speeds at a height of 50 m. These wind speeds are converted into wind speeds at 150 m height, the assumed future hub height. The common model to characterize this conversion is the logarithmic wind shear law.[16] Roughness lengths that are used have been provided by DLR as mentioned above. For the simulation of wind power plants it is assumed that new power plants will be built with the highest and most powerful wind turbines available on the market today. The power curve of the largest ENERCON wind turbine E-126 has been used as reference. This turbine offers a rated power of 7,500 kW, a typical height of 135 m and a storm control which would enable reduced turbine operation in the event of extremely high wind speeds, and prevents the otherwise frequent shutdowns and resulting yield losses.[17] For this work, the power curve has been replicated and used for the model. Finally, the air density is taken into account. The described power curve is only valid for an air density of ρ_0=1.225 kg/m³. Power changes with differences of air densities. To convert the results for the real density the ratio of real to normalized air density is used. Real air density is calculated with data of air pressure and temperature. As the power changes in dependence on the air density respective adjustments have to be included into the model. Two fundamental impacts of the air density on the power curve can be observed: as first order effect a linear reduction of the power with the ratio of local air density to that of sea level and as second order effect a shift of the power curve to higher wind speeds. Due to lack of respective data the second order effect is not included in the model. Finally, the power change is considered proportional to the air density. The resulting power generation is scaled to match with the assumed 1 GW installed capacity per 1°x1° area of the simulation grid and therefore multiplied by a factor of about 133.

Availability of wind power plants is given by the time that a wind turbine is working. This time is influenced by failures or by very high wind speeds when the power plant is turned off. Availabilities have been analysed by Faulstich et al.[18] The assumed availabilities in this paper are based on their results and amount to 95% onshore. To include the availability in feed-in a random function has been used to avoid influencing high peaks. 5% of the hours are chosen randomly and set to zero. Another way to include availability would be to reduce power consequently by 5%. The second approach might be more reasonable since not only one power plant is assumed but more than 133 and the chance that only one or two are stopped is much higher than all at once. Nevertheless, the more conservative first approach has been taken into account.

The calculation for the power generation by PV modules is based on a model described by Huld et al.[19] This comprehensive model takes into account several parameters affecting module efficiency such as temperature and irradiation. However, the published model parameters are restricted to crystalline silicon photovoltaic modules. The yield of PV power plants is increased by installing the modules optimally tilted. This means they are placed with a slope that causes the best average irradiation angle and guarantees the highest yield for the year. The coefficient of improvement that is achieved by tilting the modules over a horizontal installation was calculated for each month by Breyer [20,1], and is now used for the simulation of a PV power plant. The inverter, assumed for this work, is the Sunny Central 1000 MV manufactured by SMA Solar Technology AG. It represents one of the most installed inverters in the PV market. Based on a model of Schmidt et al. [21] a function of the inverter efficiency was simulated. PV module performance deteriorates over time. A degradation of 0.3% per year is considered in this paper. Since the simulated power plant shall be representative for every year, a medial degradation for 25 years is used. The amount of 25 years is based on the supposition that this is the expected lifetime of a solar power plant. Some other aspects have to be considered to get the final power output of the PV power plant. These are e.g. clouding, snow and pollution. An additional reduction of the generated power by 3% is assumed to account for the cumulated effects that reduce the overall performance but cannot be addressed in detail.

Power generation of PV and wind power plants is normalized to full load hours (FLh) and aggregated for periods of months and years. For this, hourly power feed-in has been added up for a year and divided by the rated power. Such data enable the extraction of overlap FLh of PV and wind power plants in order to eventually derive the critical extent of these overlap FLh (Equation 1).

$$FLh_{OL} = \left(\sum_{i=1}^{8760} min\left(P_{PV,i}, P_{Wind,i}\right) \right) \cdot 1GW^{-1}$$

$$FLh_{COL} = \left(\sum_{\forall i \in \{(P_{PV,i} P_{Wind,i}) > 1GW\}} P_{PV,i} + P_{Wind,i} - 1GW \right) \cdot 1GW^{-1}$$

Equation 1: Definition of overlap and critical overlap full load hours. Abbreviations stand for: full load hours (*FLh*), overlap (*OL*), critical overlap (*COL*), hours of the year (*i*), power (*P*), photovoltaic (*PV*) and wind power (*wind*).

Critical overlap FLh are defined by the dimension of the grid. In this work it is assumed that the grid has to be designed for the capacity of at least one of the two power technologies within a region of 1°x1° of latitude and longitude. This is why critical overlap FLh have been identified for the amount of feed-in power exceeding the rated power of either PV or wind power plants equally installed in respect to rated power capacity within a region of 1°x1° of latitude and longitude. Overlap and critical overlap have been calculated for every hour and added up to FLh, too. Calculations have been done for all years between 1984 and 2005 and are represented here by results of the exemplary year 2005.

4 RESULTS

4.1 AVAILABILITY OF RESOURCES

The global energy supply potential of PV and wind power by far exceeds the energy demand of human mankind. Long-term annual averages can be derived to indicate the resource availability on a global scale. Figure 1 shows this for GHI. Due to the irradiation conditions, the total amounts increase from the polar caps towards the equator. Another influencing factor for the occurrence of GHI at the ground is the elevation above sea level. The higher the location, the less atmosphere has to be passed. Caused by tropical climate which leads to higher evaporation from oceans and thus to clouding and rain, irradiation at the equator is lower than at regions north and south of it.

Figure 2 shows the resource availability for wind. Apart from global wind systems, the major influence on the wind speed above ground is the surface roughness length. Therefore, high wind speeds are observed above areas such as oceans and deserts. On the other hand, in the equatorial regions high roughness lengths and consequently low wind speeds are observed.

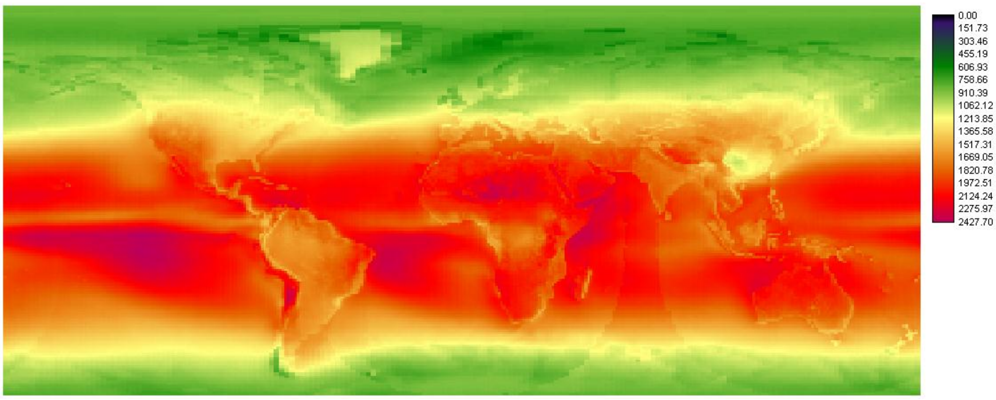


Figure 1: Annual long-term average for global horizontal irradiance (GHI; in kWh per m² and year).

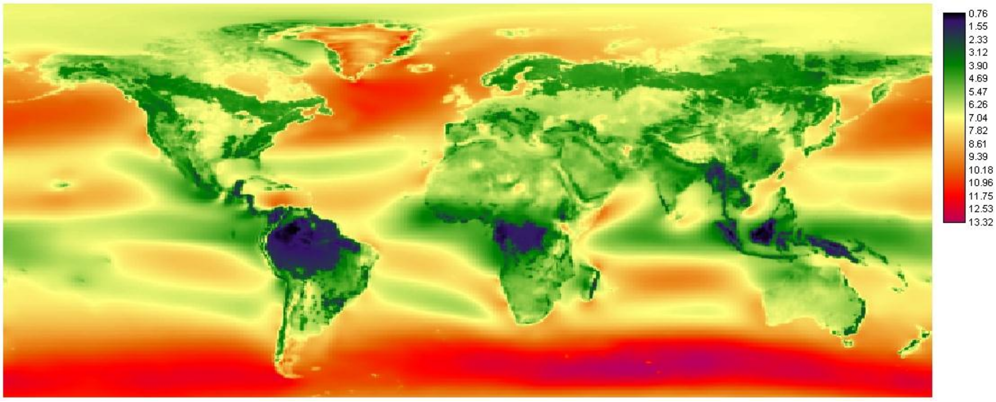


Figure 2: Annual long-term average for wind speeds (in m per s).

4.2 POWER FEED-IN

By using simulations of PV and wind power plants (section 3.2) it is possible to get hourly feed-in of prospective power plants (Figure 3). For analysing purposes the respective rated power capacities of PV and wind power plants are set to 1 GW per 1°x1° grid box. Simulating a fixed optimally tilted PV power plant and a wind power plant of 150 m hub height, of 1 GW respectively, generates the hourly feed-in power potential for all hours within the 22 years data series.

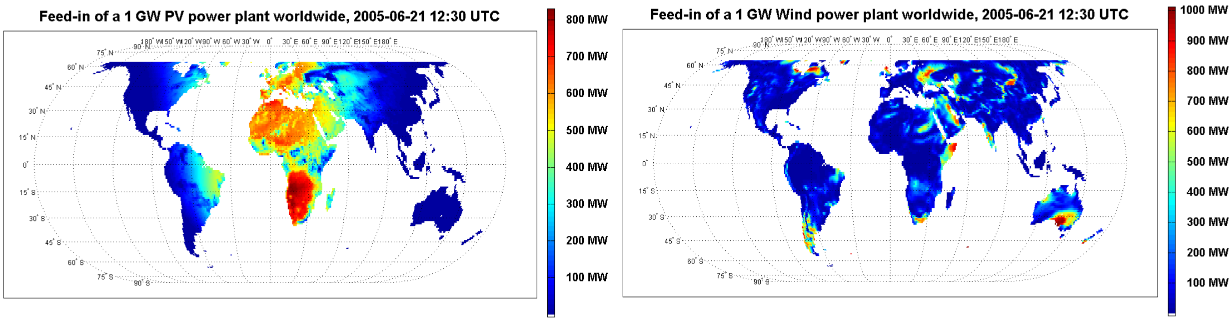
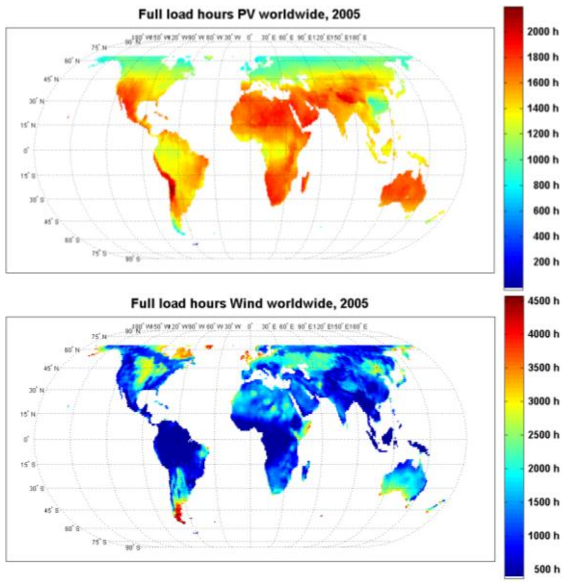


Figure 3: Feed-in power potential of 1 GW installed PV (left) and wind power (right) capacity according to historic data. These illustrations show feed-in of a certain hour which is between 12 and 13 UTC, 21st of June 2005.

Figure 3 shows conditions at one of these hours which is between 12 and 13 UTC, 21st of June 2005. At this time the sun passes the Greenwich meridian and the other hemisphere of the earth is dark, reflecting no feed-in. At the same time, wind power is high in parts of Australia and north-east Canada. Further there are some regions in Somalia, Saudi Arabia and Eastern Europe that show high wind feed-in. It is conspicuous that these areas show less PV feed-in.

4.3 FULL LOAD HOURS

The feed-in data lead to annual aggregated full load hours for both energy technologies. These are presented in Figure 4.



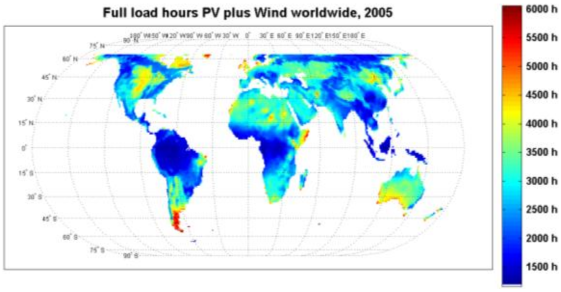


Figure 4: Full load hours of fixed optimally tilted PV power plants (top), of wind power plants of 150 m hub height (center) and of hybrid PV and wind power plants (bottom). Calculations are performed for all hours of the year 2005 and all coordinates of a 1°x1° mesh of latitude and longitude within 65° N/S.

Due to the occurrence of GHI, the PV plot of Figure 4 shows that places with most FLh are north and south of the equator, but not at the equator itself. This effect is caused by the tropical climate. Even though there is the most direct irradiation, there is not the highest yield at the equator. In fact, this direct irradiation causes more evaporation from oceans and that leads to clouding and later to rain. Irradiation on the ground decreases with clouding and so less FLh are generated in the tropics. In the far northern and southern hemisphere the FLh reduce greatly due to increased seasonal variation and, hence lower GHI. Full load hours of wind power are low at the equator and increase towards the polar caps. At the equator the wind has its least FLh. Also conditioned by climate, winds on the hemispheres turn around before they reach the equator. Comparing both plots for PV and wind power in Figure 4, it is evident that mostly those places with much wind have less PV FLh and vice versa. The addition of PV and wind FLh in Figure 4 shows that areas with high amounts of both PV and wind FLh are quite rare. Examples are southern Argentina or the eastern coast of Somalia. The overlap of PV and wind power defined in Equation 1 is shown in Figure 5.

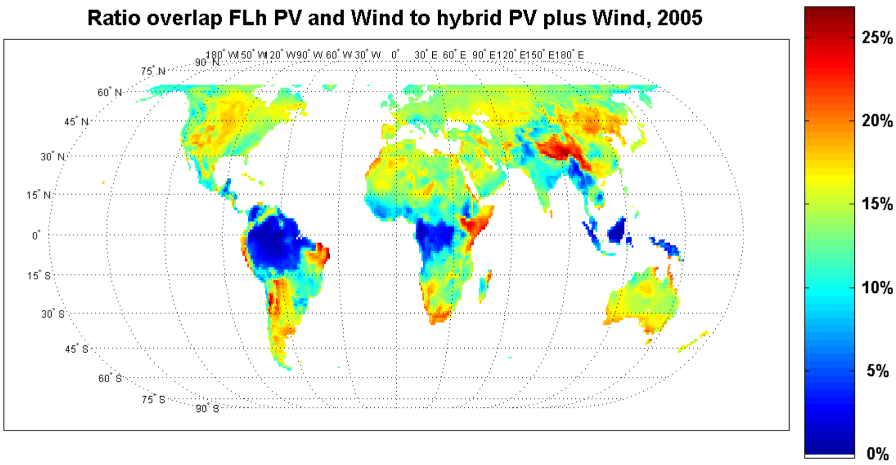


Figure 5: Ratio of overlap full load hours of fixed optimally tilted PV power plants and wind power plants of 150 m hub height to the sum of PV and wind full load hours. Calculations are based on results depicted in Figure 4 and definition in Equation 1 and are performed for all hours of the year 2005 and all coordinates of a 1°x1° mesh of latitude and longitude within 65° N/S.

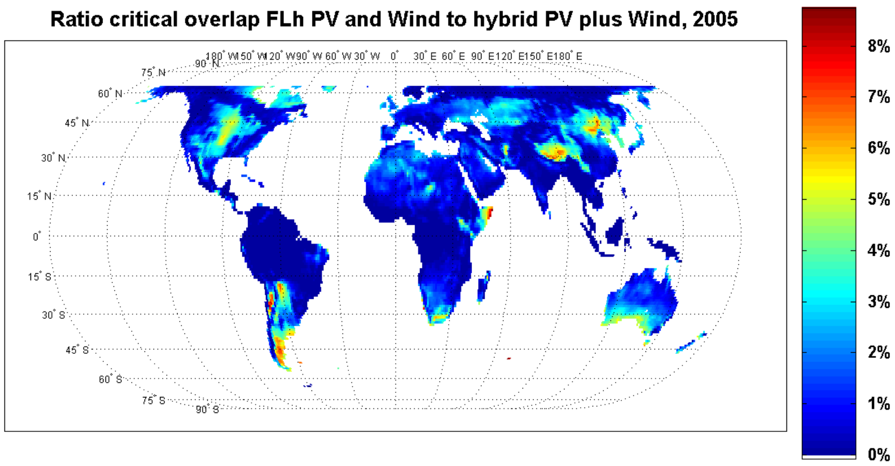


Figure 6: Ratio of critical overlap full load hours of fixed optimally tilted PV power plants and wind power plants of 150 m hub height to the sum of PV and wind full load hours. Calculations are based on results depicted in Figure 4 and definition in Equation 1 and are performed for all hours of the year 2005 and all coordinates of a 1°x1° mesh of latitude and longitude within 65° N/S.

Global average of the ratio of overlap FLh to the sum of PV and wind power FLh is about 15% ranging between 5% - 25%. High overlaps, for example, occur in southern China, in Somalia and Ethiopia as well as in eastern Brazil or north of Argentina and Bolivia. Very little to no overlap is visible at the equator. This comes from the low wind FLh in this region. Finally the amount of critical overlap FLh is counted and displayed in Figure 6.

Critical overlap FLh are defined for that amount of feed-in power exceeding the rated power of either PV or wind power plants installed within a region of 1°x1° of latitude and longitude (Equation 1). This is the power for that the grid has to be dimensioned, at least the exceeding power would have to be regulated and counted as energy loss. The figure shows that energy losses worldwide would amount to less than 9%. However there are only few regions with high critical overlap since at most places critical overlap does not exceed 3% - 4%. Those few regions that have a higher critical overlap than 5% can be found on earlier maps, basically because of high amounts of wind FLh.

5 CONCLUIONS

According to this work's approach, it can be stated that PV and wind power are energy technologies which complement one another. For places where both resources are available to build power plants, it is strongly recommendable for plant operators, manufacturers and respective associations to work together for fast growing PV and wind power capacity. Due to nearly no competition in time resolved power feed-in of PV and wind power plants, a perfect basis is given for a comprehensive cooperation. Using both energy technologies will offer complementary power feed-in and further reduces the need for balancing power.

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