PV AND WIND POWER – COMPLEMENTARY TECHNOLOGIES

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1. 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 become competitors or allies. Time resolved geospatial data of global horizontal irradiation (GHI) and wind speeds are used to simulate the power feed-in of PV and wind power plants on 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 has been defined and identified as ranging between 5% and 25% of total PV and wind power feed-in. Critical full load hours have been defined and discussed. Energy losses that would appear if the grid was dimensioned only for one power plant of PV or wind, do not exceed 9% of total feed-in but are mainly around 3%-4%. Thus the two major renewable power technologies are characterized by complementing each other.

2. 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 yet not 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 energy 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 (Breyer, 2011).

3. Solar and Wind Resource Availability

The global energy supply potential of PV and wind power exceeds by far the energy demand of human mankind. Total primary energy demand has been about 151,200 TWh_{th} in the year 2008, i.e. about 17 TW of continuous energy flow (IEA, 2010). However, substantial amount of this primary energy demand 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 (Jacobson and Delucchi, 2009). 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. In 2003, the German Advisory Council on Global Change (WBGU) derived a harvestable energy flow potential for wind power of about 90 TW and a practically unlimited potential for PV. 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 hence also for PV (WBGU, 2011). In the 2008 ‘energy [r]evolution’ study of Greenpeace the utilizable energy flow has been estimated to about 35 TW for wind power and 150 TW for PV (Teske et al., 2008). Also in 2008, Sawin and Moomaw estimated the energy flow potential to about 145 TW for PV and about 55 TW for wind power. In 2009, Lu et al. estimated the energy flow for wind power to about 80 – 150 TW. Jacobson and Delucchi (2009) derived an energy flow of 40 – 85 TW for wind and 580 TW for PV. In 2011 the IPCC derived a theoretically utilizable energy flow of about 190 TW for wind power and about 120,000 TW for PV. 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 (Kohn, 2010). The insight of the necessity to establish a solar powered society dates back many decades and was emphasized for instance by Hubbert already in 1949.

4. Methodology

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 through 2005) are provided by NASA (Stackhouse and Whitlock, 2008) 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 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 (z_0), 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 z_0 is and the bigger 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 also have 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 has been recalculated to get more realistic values for daytimes. Based on conclusions of AlBusairi and Möller (2010) and of Montes et al. (2010) 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 temperatures longer than earth and leading to a steadier climate.

Key assumptions for PV power plants are: crystalline silicon modules, leading state-of-the-art inverter technology and typical conditions for shading, dust and overall power plant configuration. Key assumptions for wind power plants are: leading state-of-the-art gearless wind turbines and very good power plant availability.

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 enables the extraction of overlap FLh of PV and wind power plants in order to eventually derive the critical extent of these overlap FLh. Problematic FLh are defined by the dimension of the grid. The assumption of this work is 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 problematic FLh have been identified for the 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. 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 exemplarily year 2005.

5. Results

5.1. Availability of resources

The global energy supply potentials of PV and wind power exceed by far the energy demand of human mankind. Long-term annual averages can be derived to indicate the resources availability on a global scale. Fig. 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.

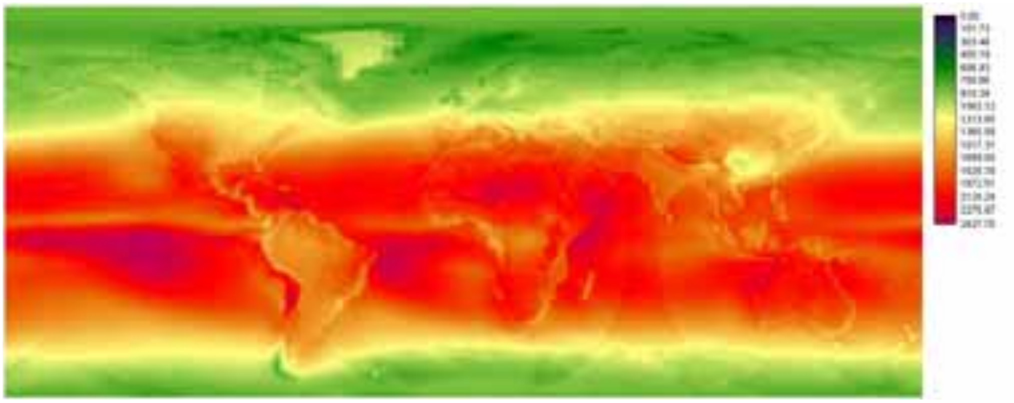


Fig. 1: Annual long-term average for global horizontal irradiance (GHI; in kWh per year).

Fig. 2 shows the resource availability for wind. Apart from global wind systems, the major reason which influences 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.

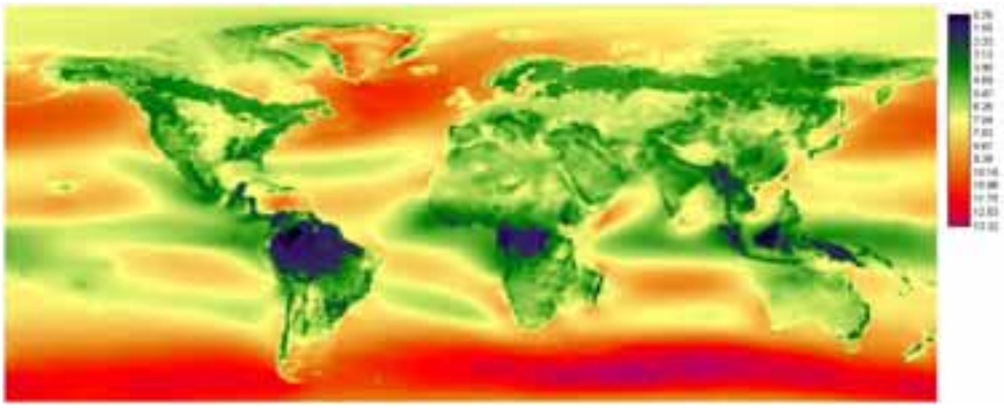


Fig. 2: Annual long-term average for wind speeds (in m per s).

5.2 Power feed-in

By using simulations of PV and wind power plants it is possible to get hourly feed-in of prospective power plants (Fig. 3). For analyzing 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.

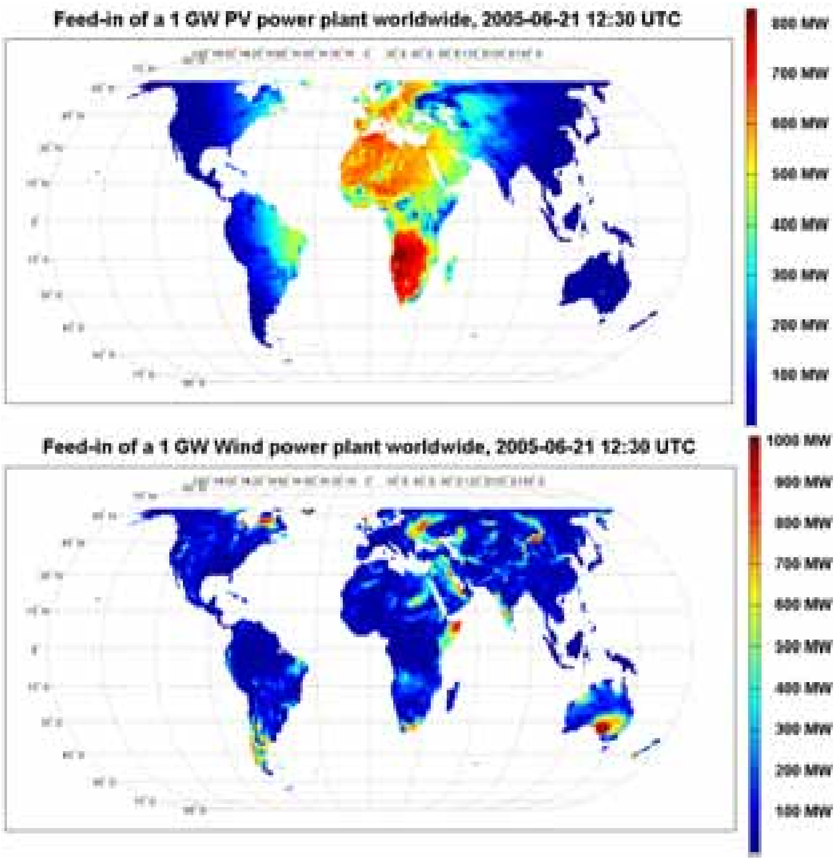
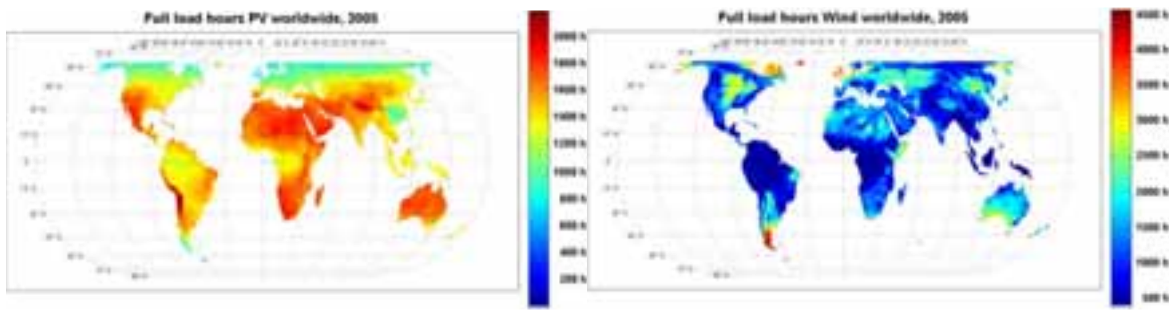


Fig. 3: Feed-in power potential of 1 GW installed PV (top) and wind power (bottom) capacity according to historic data. These illustrations show feed-in of a certain hour which is between 12 and 13 UTC, 21st of June 2005.

Fig. 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 reflected by 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.

5.3 Full load hours

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



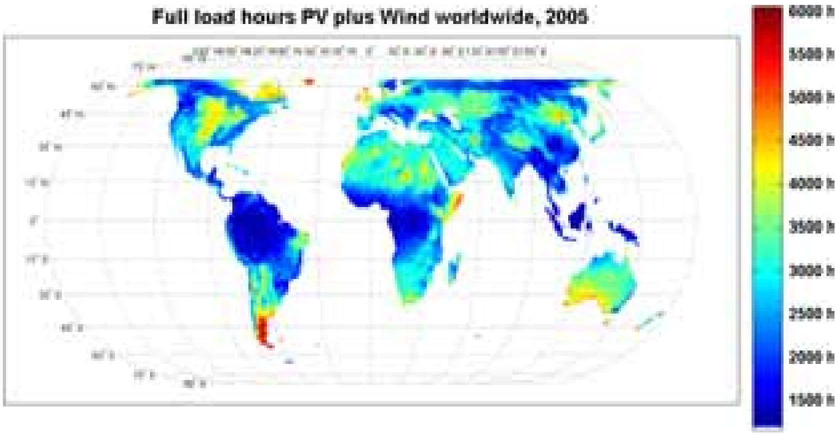


Fig. 4: Full load hours of fixed optimally tilted PV power plants (top, left), of wind power plants of 150 m hub height (top, right) and of hybrid PV and wind power plants (bottom). Calculations are performed for all hours of the year 2005 and all coordinates of a 1°x1° mesh of latitude and longitude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

Due to the occurrence of GHI, amounts of PV full load hours increase from the polar caps towards the equator but decrease at the equator itself. Full load hours of wind power are low at the equator and increase towards the polar caps. This is the opposite behavior of PV FLh and shows the complementary nature of the energy sources.

The overlap of PV and wind power is shown in Fig. 5.

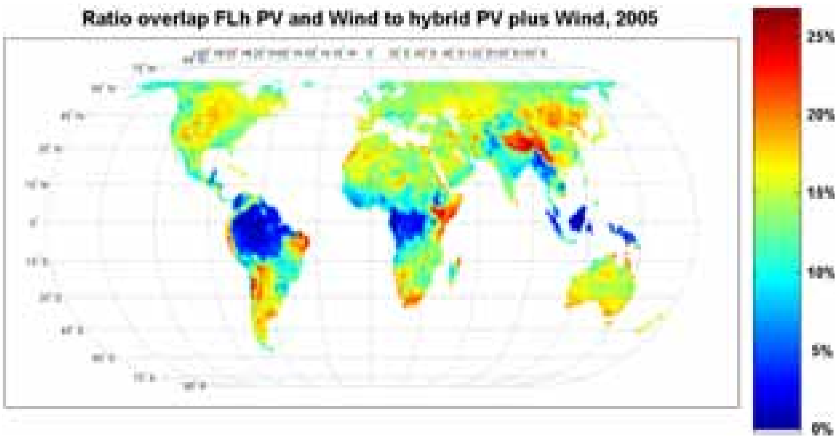


Fig. 5: Ratio of overlap full load hours of fixed optimally tilted PV power plants and wind power plants of 150 m hub height to the sum of PV and wind full load hours. Calculations are based on results depicted in Fig. 4 and are performed for all hours of the year 2005 and all coordinates of a 1°x1° 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%.

Finally the amount of critical FLh is counted and displayed in Fig. 6.

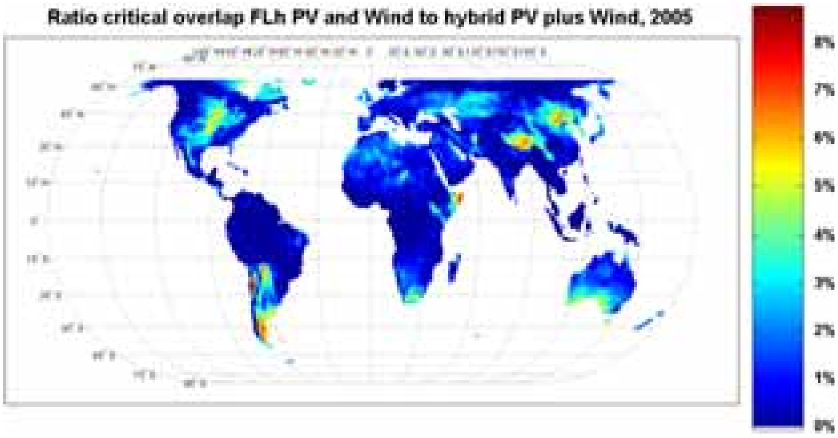


Fig. 6: Ratio of critical overlap full load hours of fixed optimally tilted PV power plants and wind power plants of 150 m hub height to the sum of PV and wind full load hours. Calculations are based on results depicted in Fig. 4 and are performed for all hours of the year 2005 and all coordinates of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

Critical 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. This is the power for that the grid has to be dimensioned, at least. 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%.

6. Conclusion

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.

7. References

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