Ramp Rates of Building-Integrated Renewable Energy Systems

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Abstract- This article analyses the ramp rates of household electricity consumption and the power production of building-integrated PV panels and wind generators. These aspects are important for the optimization of energy storage and demand-side management in buildings with prosumer status. The output power data from PV panels and a wind generator from the same building were used. It was found that the yearly standard deviation of solar energy output is greater than the standard deviation of output from the analyzed wind generator but the ramp rates are higher for the wind turbine. Ramp rates of the solar energy power plant have a slower rising slope comparatively to the same parameter from the wind generator. This shows higher temporal stability in PV output, which was also validated with autocorrelation functions.

Keywords- Electricity consumption, wind generator, photovoltaic array, output fluctuations, ramp rates.

NOMENCLATURE

l	Time lag between values
P_n	nominal power
r(l)	autocorrelation function
x_i	values in a time series
$\bar{x}$	mean of the time series
CDF	cumulative distribution function
PV	photovoltaic
WG	wind generator

1. Introduction

The stochastic nature of large wind generators (WG) and photovoltaic (PV) power plants is evident from earlier research [1], [2] and changes in output power of building-integrated PV and wind generators are described in [3]–[5]. The stochasticity of WG output is caused by sudden wind gusts and turbulence [6], [7] on the other hand fast changes of out from PV panels are caused mainly by the movement of clouds [8], [9]. This can affect the voltage stability in the distribution grid [10]. One proposed solution to mitigate this problem is the geographic dispersion of generation units [11], another one is storage [12][13].

The stochasticity of those energy sources has been compared on the scale of European countries [11], but even if we assume that the large scale fluctuations could be mitigated by robust interconnections between countries, then the local issues like voltage quality and economic factors related to renewable energy self-consumption remain [14]–[17]. These topics are especially topical because of regulations that incentivize the installation of renewable energy generation devices on all new buildings [18].

Hourly average values are often used for the modelling of small renewable energy systems, which gives the impression that the energy generation and production during an hour are constant, but renewable energy sources have significant intra-hourly fluctuations [19]. The use of hourly average data series may result in models that appear more stable than the reality that they describe [20]. The hourly time resolution is somewhat acceptable in describing processes that occur in the transmission grid, because of the large number of interactors that use the transmission and distribution grids, but a higher time resolution could be beneficial even there [21]. Energy is currently commercially measured as hourly averages ("Nordpool spot Electricity price,"). In the same time, it is foreseeable that data acquisition with higher resolution will be necessary to facilitate the needs of distributed energy generation and use the full potential of remote metering possibilities. The application of real-time tariffs in the future is also a possibility [22]. The novelty of this paper lies in the application of analysis methods on building based energy systems which are until now only used on grid-scale facilities, like wind parks.

The aim of this study is to demonstrate the rate of changes in both, the consumption and production output in building integrated energy systems. The results can be used to optimize energy management and storage possibilities for different building-integrated WG and PV applications.

2. Materials and Methods

2.1. Data

WG and PV output variability is in strong relation to local weather conditions. The study compares the technologies in a case study where both are in the same location in a city. Differences in wind resources are more influenced by surrounding obstacles, and solar irradiation conditions are more dependent on the atmospheric conditions (cloudiness). The measurements were conducted in an urban environment at (58°23'19'' N, 26°41'37'' E), PV panels were faced directly to South at a 40-degree tilt and the hub height of the WG was 25 m. The technical specifications of the used devices and measurement system are shown in Table 1.

Table 1. System specifications

Device	Specification
Wind generator (WG)	WindSpot 3.5, Horizontal axis, 3.5 kW, permanent magnet generator, passive yaw control [23]
WG inverter	SMA Windy Boy 3600TL [24]
Photovoltaic (PV) panels(10 panels)	Yingli solar 245 W [25]
PV inverter	Solivia 2.5 EU G3 [24]
Measurement system	Janitza UMG 605 [26], Circutor P2 TC5 M70312 [27]

The power output data was logged with 250 ms integration periods and a sample of the PV inverter output during an example day is shown in the next figure (Fig. 1).

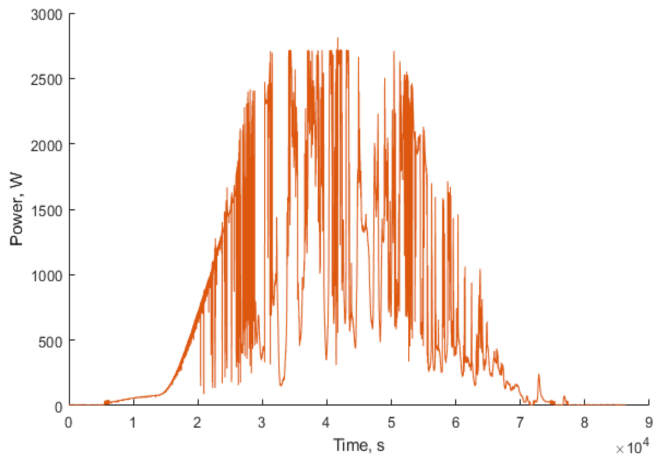

Fig. 1. PV-array output on a sample day (June 18-th 2014, 250 ms integration period).

The PV output changes shown in Fig. 1 are caused by cloud movements whereby WG output changes (Fig. 2) are caused by changes in wind direction and speed [28].

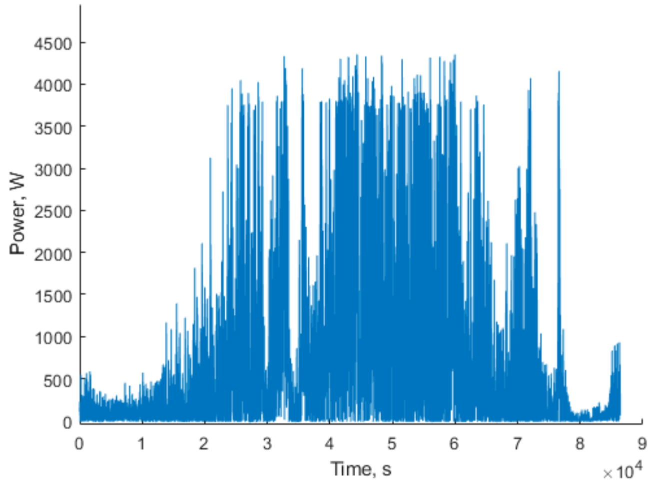

Fig. 2. WG output on a sample day (June 18-th 2014, 250 ms data).

The WG output changes are very frequent and fast during the day, and for the comparison of the energy sources, a characteristic 60-minute fragment of WG and PV data is presented in Fig. 3.

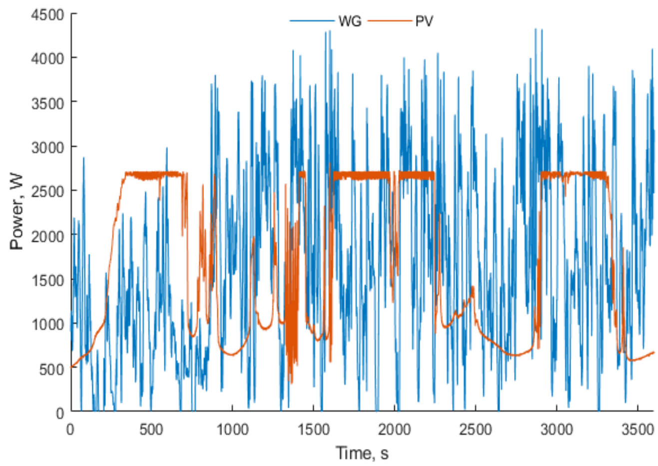

Fig. 3. Sample WG and PV data with 250 ms integration period.

Fig. 3 shows an output power section during the midday when both energy sources reach their nominal power. It supports the hypothesis that PV output is more stable than WG output. The opposite side of the analysed small energy system, the consumption pattern, is presented in the next figure (Fig. 4).

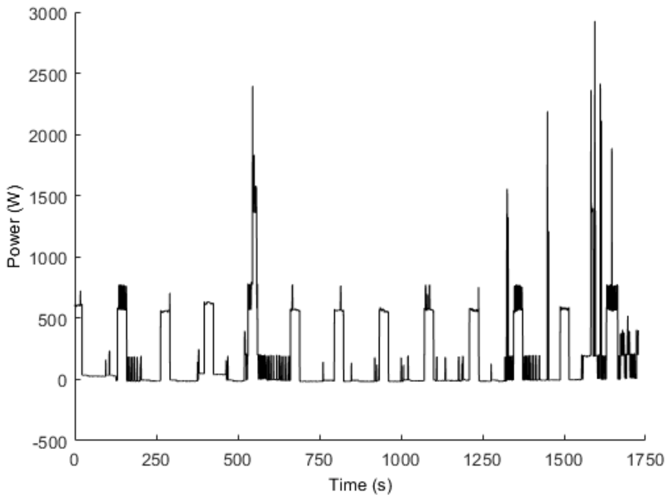

Fig. 4. Sample consumption pattern.

Additionally, for the long-term analysis of the energy producers, 5-second integration periods were used. This integration period was chosen because the yearly data amount remained in manageable confines and still offered the necessary information about variability.

2.2. Methods

The data was normalized for better comparability, by dividing the data series by the nominal power of the devices. For the generation devices, only the values greater than zero were used in the analysis, because extended periods of no output would give the impression of higher output stability. For example, the night-times of the PV and the wind-lulls of the WG were eliminated. On the other hand, consumption power is almost never zero because of base loads like internet routers or surveillance systems. Standard deviation figures were used to analyse the amplitude of changes in the data series [29], ramp rates enable the analysis of rapid short term changes in the time series and autocorrelation functions enabled the analysis of the temporal continuity of the time series.

A ramp rate is defined in the context of the current article as the speed of change in consumption or production capacity up or down during a given time period [30]. If the power decreases then the process is defined as ramping down and in the opposite situation it is ramping up.

Further, we used autocorrelation functions to analyse the pace of changes by comparing the correlation of the time series with themselves under different time lags [31]. Autocorrelation functions have been used in renewable energy-related research to show the changes in daily and yearly wind speeds and temperatures [32], [33]. The Pearson's product-moment based autocorrelation function r(l) dependent on time lag (l) was calculated with the following equation [34], [35]:

$$r(l) = \frac{\sum_{(i=1)}^{(N-l)} (x_i - \bar{x})/(x_{i+1} - \bar{x})}{\sum_{(i=1)}^{N} (x_i - \bar{x})^2} \quad (1)$$

where, l is the lag, which is the time distance between pairs of values in the analysed time series, xi are the values and x̄ is the mean of the time series. The interpretation of correlation coefficients is described in [36].

3. Results

Standard deviations of the output power of the analyzed energy generation devices are presented in (Table 2).

Table 2. Output characteristics of the analysed energy generation devices

	Technology	
Statistical parameters	**Photovoltaic**	**Wind generator**
Mean power when in operation (% of P_n)	32.58 %	13.20 %
Standard deviation (% of P_n)	31.07 %	13.56 %
Maximum daily standard deviation (% of P_n)	63.05 %	23.18 %

Ramp rates of the output power were found for further analysis. Fig. 5 presents the solar energy production with normalised ramp rates.

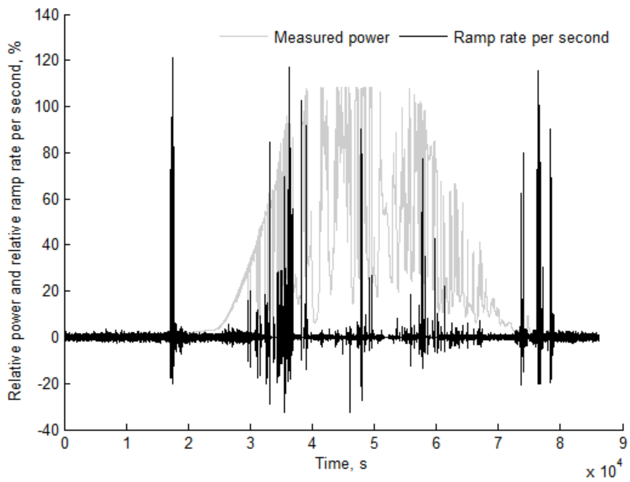

Fig. 5. PV output power in relation to nominal power and ramp rate in relation to previous time step during a sample day.

A cumulative distribution function (CDF) was created for further analysis of the ramp rates presented above (Fig. 5), which is given in the next figure (Fig. 6).

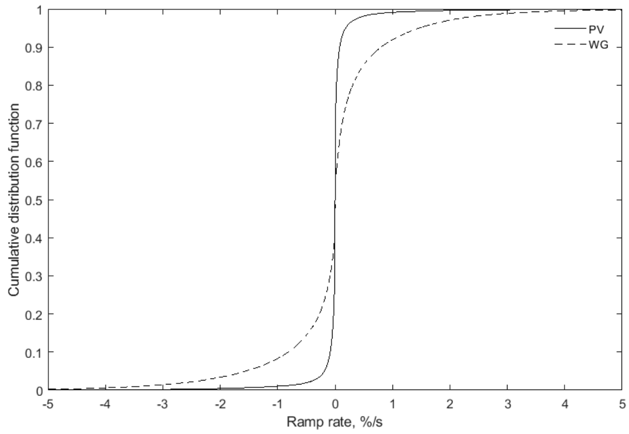

Fig. 6. Cumulative distribution function of PV and WG output rates of changes.

The CDF shows visually, that negative and positive ramp rates have a similar distribution shape, although turned upside down (Fig. 6), which means that the power outputs of the analysed energy sources increase at a similar pace as they decrease. The CDF-s presented in Fig. 6 also confirm that the WG has more frequent and higher ramp rates than the PV. For example, 10 % of the WG's ramp-up and ramp-down occurrences are greater than 1 %·s-1, while 10 % of the most extreme PV ramp up and down rates are greater than 0.1 %·s-1. Consumption power is much more stable, as can be seen from the CDF of the consumption ramp rates presented in the next figure (Fig. 7).

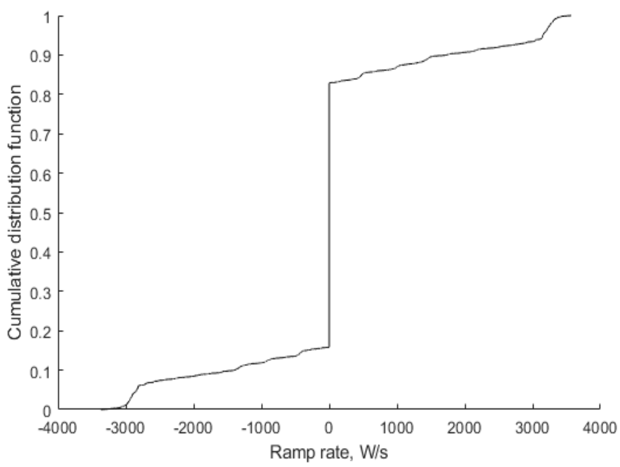

Fig. 7. Cumulative distribution function of changes in consumption power.

Fig. 7 shows that in 15.8 % of the time steps the consumption power is decreasing and 17.06% of the time power is increasing, which means 67.14% of the time (on a timescale of seconds) the consumption is stable, or the changes are imperceptible. The periods with stable output power are characterized in Fig. 7 by the horizontal line in the centre. By comparing Fig. 6 and Fig. 7 it can be concluded that the energy consumption has by far more time steps with stable power in comparison to energy production.

The autocorrelation analysis of the production output further shows that there are faster fluctuations of WG output in comparison to the PV output (Fig. 8). Autocorrelation plots of WG power during longer periods show that their autocorrelations have a 24-hour cycle [37].

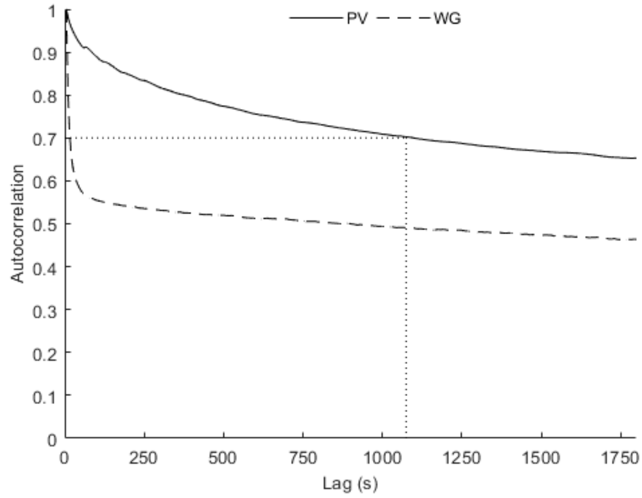

Fig. 8. Autocorrelation functions of PV and WG output data with 5-second integration periods [38].

Fig. 8 shows that the maximum autocorrelation lag, during which the PV output has a strong autocorrelation (≥ 0.7), is 1040 s. As a comparison for WG output, the maximum lag with the same autocorrelation threshold (≥ 0.7) is 40 s. The decrease in the strength of the autocorrelation for WG is faster than for the PV. On the basis of Fig. 8 and Fig. 9 can be concluded that building integrated PV installations have in this case higher stability of output than building integrated WGs. The periods of fast changes in the WG output are probably caused by wind turbulence in the surroundings. PV panels are not as much affected by the local microclimate. Fig. 8 shows that the fastest decrease of the autocorrelation values occurs on time lags up to 1000 s, which is most likely caused by wind speed and direction changes that affect the WG output short term. 250 ms data from a sample day (Fig. 9) shows a similar situation the autocorrelation function as 5 s data from a whole year (Fig. 8).

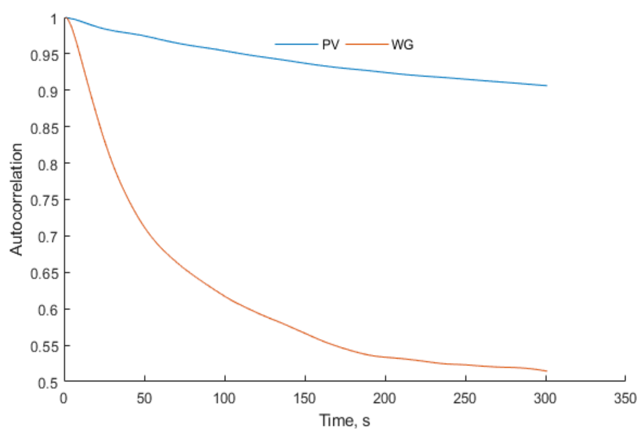

Fig. 9. Autocorrelation functions of a PV array and WG output data with 250 ms integration period [38].

By comparing the standard deviations of the normalized PV and WG outputs in Table III it is also evident that the standard deviation of PV output is higher. The analysis of daily averages shows that deviations between days are highest in the month of March. The highest intraday standard deviation of output occurs from the PV panels on days with active cloud movement but on average the PV output is more stable than the output from the wind generator. The WG output is in direct relation to wind speed, and in the case of the analysed building-integrated WG the rotor inertia had no significant effect on the output stability. The output stability of building-integrated WG is strongly correlated to the wind conditions in the area [38].

4. Discussion

The above-stated hypothesis was confirmed to be true that PV panels have higher output stability than wind generators in the same geographical location. Furthermore, the consumption power of the building has a much higher stability than the production power of the energy generation on the building. This issue is especially important in regard to the direct consumption and storage of locally produced renewable electricity.

There are several possibilities to cope with output fluctuations like shown in Fig.1 and Fig. 2. These are capacitors [39], demand management with power electronics [40], increase transmission capability of distribution grid [41], [42] or batteries [43], [44].

Each of these methods has advantages and disadvantages for the mitigation of short-term fluctuations. The use of demand management of electronic applications or white goods in residential buildings (Table 3) is not feasible for the utilization of local peak power production (Fig. 1 to Fig. 3), because the output peaks of small renewable energy systems are generally too short in duration for this (Fig. 8).

Table 3. Work cycle durations of household appliances [45]

Appliance	Cycle duration (min)
Refrigerator	30
Heat pump	15
Dish washer	60
Washing mashine	120

Storage devices in cooperation with demand-side management are needed to overcome the problem that appliances have longer working cycles (Table 3) than the fluctuations of energy generation devices.

5. Conclusion

The study shows with the application of ramp rates that the electricity consumption power in building based energy systems is generally more stable than the production power of renewable energy generation devices that may be installed on the same buildings. It was also concluded that the output power of small PV panels had higher stability than the output power of a wind generator with comparable capacity in the same location. The stability of energy flows is an important factor for local energy management or energy storage optimization.

The maximum autocorrelation lag with a strong correlation coefficient (≥ 0.7) is for the PV system 1050 s and for the WG 40 s. The fastest changes can be observed in the output power of the WG and the normalized annual standard deviation is also higher for the WG.

The fluctuations are dependent of weather conditions and the daily standard deviations can vary profoundly for both of the compared technologies, the WG and PV. Especially in springtime, on days with active cloud movement and gusty winds. The findings from the article can be used for the optimization of data acquisition, short-term energy storage and demand management.

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