Optimizing the Grid Connection of Hybrid PV and Wind Power Plants

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Abstract

In order to economically optimize the grid connection of a hybrid renewable power plant consisting of photovoltaic (PV) generation and wind turbines, the simultaneity of production from both energy sources should be taken into account. In this work, high-resolution feed-in data from such a hybrid power plant was recorded and evaluated. The results allow for an estimation of maximum energy curtailment in case of an undersized point of common coupling (PCC). Additionally, it is shown how the ratio between the PV and the wind part of a hybrid power plant influences the required dimensioning of the PCC for determined accepted levels of energy curtailment. Finally, a cost comparison for a specific curtailment scenario is performed, demonstrating that it can be economically beneficial to accept curtailment in exchange for a reduced transformer size.

Keywords: Hybrid power plant, wind power, photovoltaics, curtailment, point of common coupling

1. Economical drivers for co-using grid connection points

Recent years have brought a sharp reduction of investment cost for utility-scale variable renewable energy power plants (VRE) such as wind or PV power plants, leading to levelized cost of electricity (LCOE) of less than 4 €ct/kWh for both technologies in Germany (see Kost et al., 2018), and less than 2 €ct/kWh for PV in specific projects in other countries (see Clover, 2017). In the attempt to even further reduce cost, the attention of VRE planners and builders is turning towards the connection to the electrical power grid. Several projects use the presence of an existing power plant's connection point for a cheaper grid connection of their planned VRE. An example for this is shown in Enkhardt (2017), while Gerdes et al. (2017) explain the economical boundary conditions for this reasoning.

In the case that a PV and a wind power plant share the same grid connection point and possibly even the same feed-in transformer, the state of the art is to dimension the transformer according to the joint rated power of both VRE parts together. However, it is known from previous investigation (Gerlach et al., 2011) that at least on regional or national levels, high rates of injection from wind and from PV have a rather low level of coincidence. If this is also true for individual sites, it might be worthwhile to use smaller-rated feed-in transformers and connection points while curtailing the feed-in power in the cases where both VRE do work at high power.

The goal of this investigation is to demonstrate for a realistic study case by how much the capacity of the grid connection can be reduced, and how big the total energy loss due to curtailment will be. Additionally, the optimal ratio between installed wind and PV power for obtaining a minimized power rating of the connection point and least curtailed energy at the same time is evaluated.

2. Study case and data acquisition

2.1. Description of the hybrid VRE

In order to answer these research questions on the level of an individual site, a combined PV / wind power plant situated in Eastern Germany was chosen to serve as a study case. This VRE consists of a 10.3 MWp PV park and 24 MW of wind turbines. A 20 kV switchgear connects the two feeders of the wind park and the two feeders of the PV power plant to the grid connection feeder. The VRE is connected to the 110 kV power grid via a 35 MW transformer so that the combined peak power of both power plant parts can be fed into the grid. Fig. 1 shows a sketch of the VRE's layout.

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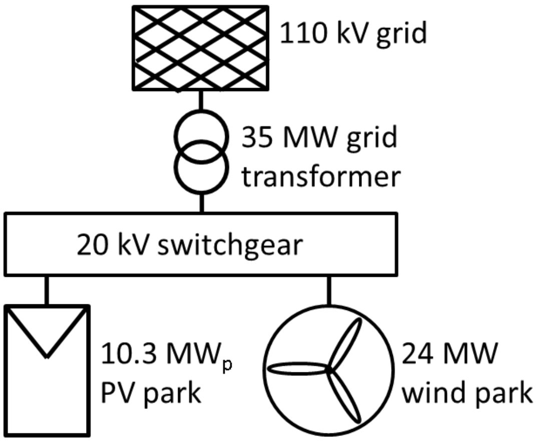

Fig. 1: Layout of the studied hybrid power plant

2.2. Data measurement and treatment

Within the park-internal switchgear, measurement devices were installed and power measurements with a time resolution of 5 s were recorded over the course of a year from Sep. 2017 to Sep. 2018. The measurement devices were positioned at all 5 feeders of the switchgear.

In order to handle this large amount of information, the raw data was treated for subsequent evaluation. The power of the feeders collecting PV and wind power was summed up respectively. That way, the total power produced by the wind turbines and by the PV power plant could be distinguished easily. Additionally, the measured data was downsampled to an effective time resolution of 1 min. A comparative sample analysis showed no relevant statistical difference between the 1 min and the 5 s data.

Afterwards, the resulting data was normalized for the further evaluation steps:

$$P_{rel}(t) = \frac{P_{meas}(t)}{P_{nom}} \qquad \text{(eq. 1)}$$

In this calculation, $P_{meas}(t)$ is the measured total power produced by either PV or wind at any given moment of time, and P_{nom} is the nominal power of the wind or the PV part of the VRE. An excerpt of the data set P_{rel} after treatment for April 2018 is shown in Fig. 2.

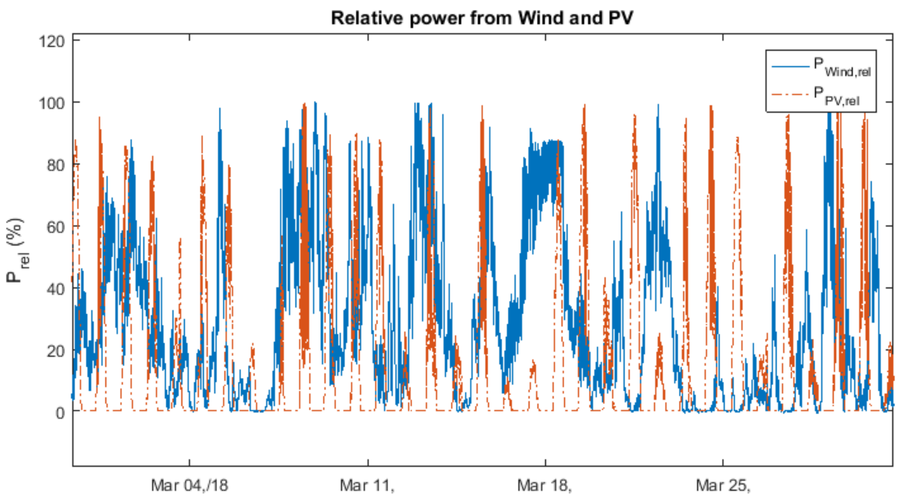

Fig. 2: Measured and treated power values for March 2018

3. Simultaneity of feed-in from wind and PV

3.1. Coincidence of production

In order to determine the simultaneity of feed-in from wind and PV for the study case, the level of coincidence of production from both parts of the VRE was evaluated.

Fig. 3 shows a graphic representation of the simultaneity of production. The data points for each minute of the year are positioned according to their wind and PV power and represented with red dots. The black lines in the upper right mark the limits of 80 % and 90 % of joint capacity respectively. It can clearly be seen that levels of high production from both VRE parts occur less frequently than other operation scenarios.

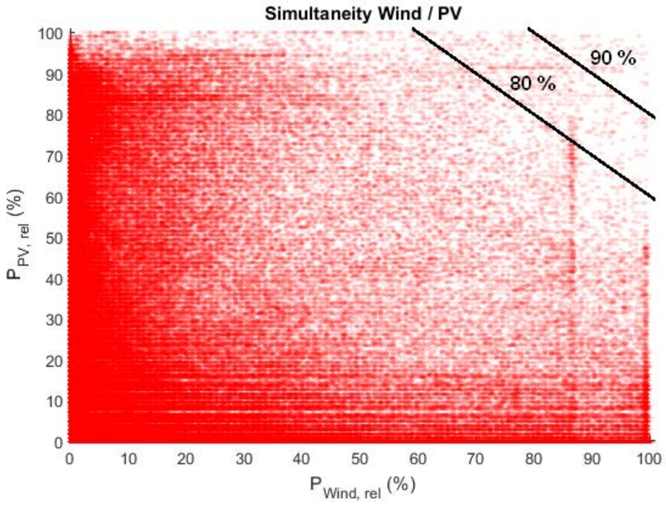

Fig. 3: Simultaneity of power production from wind and PV for study case

3.2. Curtailment times and losses

As shown in an earlier study (see Grab et al., 2019), this can be analyzed further by evaluating the relative curtailment time t_{curt} when a single wind or PV power plant or a combined wind / PV plant surpass a certain level of power P_{curt}, which is defined as a fraction of the nominal power of the plant.

$$t_{curt} = \frac{\sum t \; where \; P(t) > P_{curt}}{\sum t} \cdot 100 \,\% \qquad \text{(eq. 2)}$$

It was found that the wind power plant surpassed 80 % of its nominal power for 7.1 % of all evaluated time points. While the same was true for 3.1 % in the case of the PV part, this only occurred for 0.1 % of all time points for the combined wind / PV power plant.

If a curtailment at a certain fraction of the nominal power was implemented, the time points with the best power production would be affected. Luckily, not all of the energy harvested at these moments would be lost, but only the part surpassing the curtailment level. The energy loss can be calculated by using formula (3):

$$E_{curt} = \frac{\sum(\mathrm{P(t)} - P_{curt}) \; where \; P(t) > P_{curt}}{\sum P(t)} \cdot 100 \,\% \qquad \text{(eq. 3)}$$

In this case, a curtailment at 80 % of the respective nominal power would lead to an energy loss of 3.87 % for the wind part, 1.23 % for the PV part, and only 0.04 % for the combined power plant.

Tab. 1 sums up the relative time t_{curt} when curtailing occurs as well as the energy lost through curtailing E_{curt} for the wind part, the PV part and the combined PV / wind power plant for different curtailment levels P_{curt}.

Tab. 1: Curtailment times and curtailed energy for different curtailment powers

Curtailment power P_{curt}	Wind power plant	PV power plant	Combined power plant
40 %*P_{nom}	t_{curt} = 22.0 % E_{curt} = 27.38 %	t_{curt} = 13.8 % E_{curt} = 27.32 %	t_{curt} = 11.6 % E_{curt} = 6.67 %
50 %*P_{nom}	t_{curt} = 16.8 % E_{curt} = 18.95 %	t_{curt} = 10.8 % E_{curt} = 17.80 %	t_{curt} = 4.0 % E_{curt} = 1.98 %
60 %*P_{nom}	t_{curt} = 12.8 % E_{curt} = 12.51 %	t_{curt} = 8.5 % E_{curt} = 10.31 %	t_{curt} = 1.2 % E_{curt} = 0.63 %
70 %*P_{nom}	t_{curt} = 9.8 % E_{curt} = 7.58 %	t_{curt} = 5.9 % E_{curt} = 4.71 %	t_{curt} = 0.4 % E_{curt} = 0.18 %
80 %*P_{nom}	t_{curt} = 7.1 % E_{curt} = 3.87 %	t_{curt} = 3.1 % E_{curt} = 1.23 %	t_{curt} = 0.1 % E_{curt} = 0.04 %
90 %*P_{nom}	t_{curt} = 4.3 % E_{curt} = 1.37 %	t_{curt} = 0.4 % E_{curt} = 0.09 %	t_{curt} = 0.0 % E_{curt} = 0.00 %

It can be observed that the reduced simultaneity of production from wind and PV reduces the need for curtailment considerably. For the present study case, even a curtailment at a threshold of 50 % of the combined nominal power only leads to an energy loss of 1.98 % of the total energy, far less than for a single wind or PV power plant. This result is consistent with Gerlach et al. (2011), where energy losses of around 2 – 3 % were forecast due to “critical overlap” (which corresponds to a curtailment power level of 50 % of P_{nom} in the present study case) for many regions in the world, including most parts of Europe, the US west and east coasts, and eastern China.

This result shows that for combined PV / wind power plant, an undersized PCC and subsequent power curtailment during coinciding high levels of production from both technologies does not necessarily lead to important energy losses. The study case demonstrates that strong production from the wind part and the solar part happen very rarely at the same time, and that this is true not only for regions or countries, but also for individual sites.

4. Influence of PV and wind ratio on optimal PCC size

In chapter 3, the curtailment losses of the combined power plant were calculated following the assumption that the wind and the PV part have the same nominal power. However, this might not be the optimal case.

In an earlier study (Grab et al., 2019), it is shown how the relative dimension of the wind part and of the PV part of a hybrid power plant influence the curtailment losses for different curtailment levels. For the study case, the optimal ratio between the two VRE parts where the least energy curtailment occurs was calculated for curtailment thresholds between 40 and 90 % of P_{nom}. It was found that the ratio of 1:1 between the wind and the PV part which was analyzed in chapter 3 is already rather close to the optimum.

In this study, the analysis is reversed: For certain acceptable loss levels, the minimum curtailment threshold (corresponding to the minimum required PCC size) was calculated depending on the ratio between wind and PV of the hybrid power plant under consideration. With this knowledge, planners and investors of a hybrid power plant can assess economically which energy loss is acceptable and find the corresponding reduced PCC size for a given ratio between wind and PV.

4.1. Methodology

In chapter 3 it is described how the original feed-in data measured in the study case plant was treated. For this evaluation, the treatment was taken one step further and the data was scaled, thus providing different ratios between wind and PV:

$$P_{Wind,scale}(t) = \frac{1}{r+1} \cdot P_{Wind,rel}(t) \qquad \text{(eq. 4)}$$

$$P_{PV,scale}(t) = \frac{r}{r+1} \cdot P_{PV,rel}(t) \qquad \text{(eq. 5)}$$

In this context, r is defined as being the ratio between the nominal power of the PV power plant and the wind park after scaling:

$$r = \frac{P_{PV,nom}}{P_{Wind,nom}} \qquad \text{(eq. 6)}$$

$P_{Wind,rel}$ and $P_{PV,rel}$ are normalized measurement time series as calculated in (eq. 3).

The value of r was varied from 0.1, which represents a combined power plant with 9.1 % PV share and 90.9 % wind share, and 100, which means a combined power plant with reversed proportions (see Fig. 4). All intermediate proportions of wind vs. PV are encompassed in this exercise as specific values of r. A value of r = 1 is equivalent with a PV / wind ratio of 1:1.

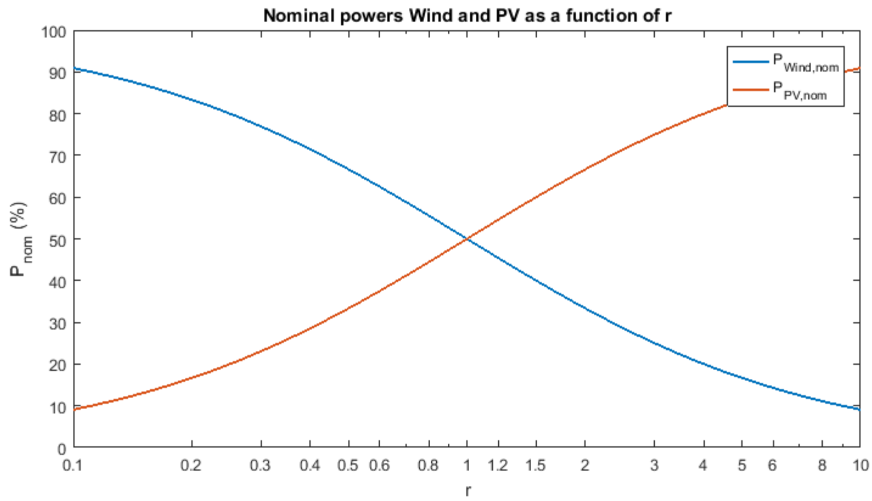

Fig. 4: Relation between ratio r and nominal powers of wind park and PV plant

In a similar way as performed in chapter 3.2, the curtailed energy was calculated for different values of r and P_{curt}. For P_{curt}, this was done in steps of 0.01 p.u. For r, values between 0.1 and 10 with a resolution of 0.01 were considered. The result is a matrix with curtailed energy values, thus enabling the identification of areas with equal energy curtailment.

4.1. Results

This evaluation makes it possible to connect points of equal energy curtailment with plot lines. Fig. 5 shows such a plot where lines of energy losses from 0.5 % to 2.5 % of the total produced energy are represented. Depending on the ratio r between the nominal power of the wind and the PV part of the hybrid power plant, determined amounts of lost energy due to curtailment can be reached for different curtailment powers P_{curt}. A ratio of 1 represents a hybrid power plant where the wind and the PV part are equally dimensioned. To the left and right side of Fig. 5, the ratios of 0.1 and 10 already hint to the situation of non-hybrid wind and PV power plants. These extremes mirror the scenario that was discussed in chapter 3. It can be observed that the ratio r between wind and PV strongly influences the value of P_{curt} (and thus the required minimum PCC size).

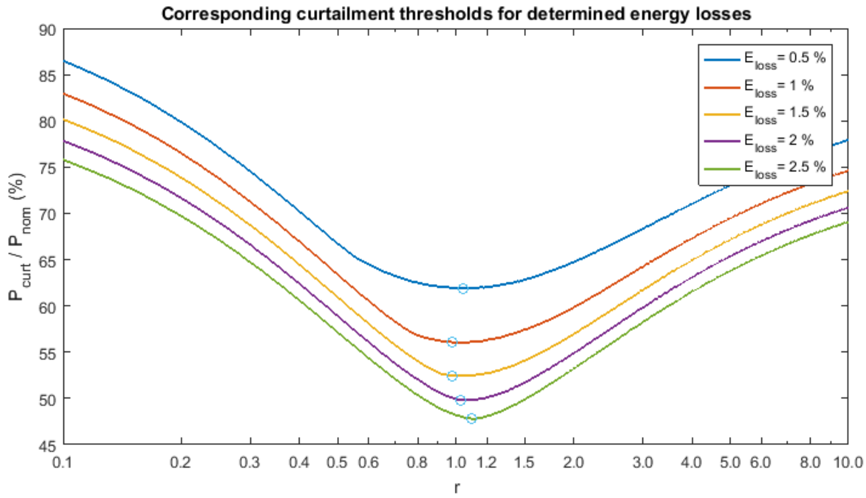

Fig. 5: Corresponding power curtailment thresholds for determined energy losses and PV / wind ratios

For a closer look, an evaluation was made where only values of r between 0.7 and 1.5 were regarded (Fig. 6). An optimal PV / wind ratio can be found for each energy loss level. In Fig. 5 as well as in Fig. 6, these points are marked with a circle. At these points, the smallest possible value for P_{curt} leads to a determined energy loss. It can be observed that optimal r values for all evaluated loss levels are close to 1. For instance, a loss level of 2 % of the total produced energy can be reached with a curtailment threshold of 49.8 % of the nominal power of the hybrid power plant if the ideal ratio of 1.03 is chosen. Generally speaking, PV / wind ratios between 0.9 and 1.3 give the best result for all evaluated energy loss levels.

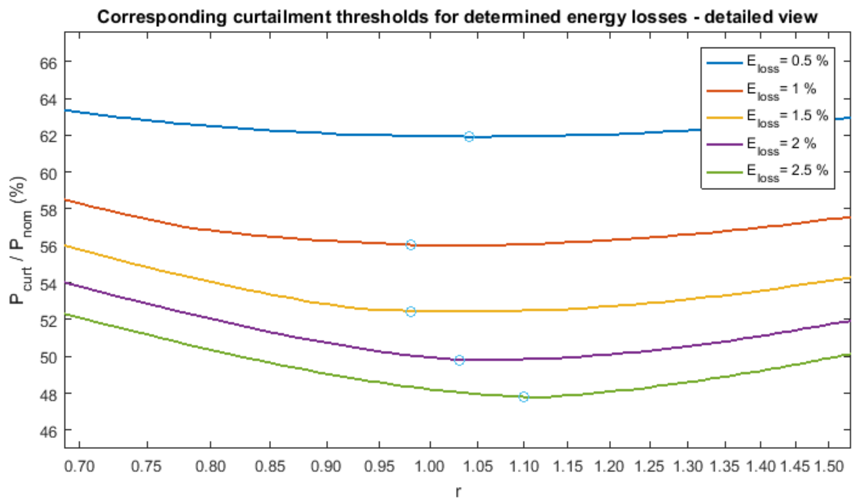

Fig. 6: Power curtailment thresholds - detailed view

Tab. 2 summarizes optimal PV / wind ratios r and resulting minimum curtailment thresholds P_{curt} for different curtailed energy levels E_{loss}.

Tab. 2: Optimal PV / wind ratios and minimum required curtailment powers P_{curt} for different energy losses

Energy loss E_{loss}	Optimal ratio $r = \frac{P_{PV,nom}}{P_{Wind,nom}}$	Minimum required curtailment power P_{curt}
0.5 %*E_{total}	1.04	61.9*P_{nom}
1 %*E_{total}	0.98	56.1*P_{nom}
1.5 %*E_{total}	0.98	52.4*P_{nom}
2 %*E_{total}	1.03	49.8*P_{nom}
2.5 %*E_{total}	1.10	47.8*P_{nom}

5. Economical undersizing of hybrid power plant connection points

When the grid connection of a VRE power plant is being planned, there are typically two factors that limit the maximum power that can be fed into the electrical grid at the connection point. First, there are possible restrictions imposed by the grid operator due to the specific capacity of the local grid. The second factor is the nominal power of the park-internal equipment, for example power converters, switchgear, or a power transformer which is used if the park-internal AC grid has a different voltage level than the outside grid.

The results derived from the study case and presented above show that for hybrid PV / wind power plants, very few energy is lost if the maximum feed-in power is curtailed at values that are considerably smaller than the combined nominal power of both VRE parts. It might therefore be economically beneficial to use equipment with less nominal power for this kind of VRE. The accumulated energy losses over the years can be compared with the savings that buying smaller equipment brings. Obviously, it must be ensured in this case that the total feed-in of the combined VRE never exceeds the power limit of the weakest component. A fast and reliable park controller which regulates the feed-in of the individual generating units should be used.

A possible approach to demonstrate these economical considerations is to reduce the size of the feed-in transformer and compare the cost savings with the revenue losses that are caused by the energy curtailment. In this study, the results from chapter 4 were used to perform this exercise.

Several assumptions and cost estimations had to be done for this evaluation. The hybrid power plant was assumed to have a total nominal power of 2 MW. In accordance with the recorded data from the study case, the specific yield of the PV power plant was assumed to be 1150 kWh/kW$_p$ and the specific yield of the wind park 1670 kWh/kW per year. This leads to a total yield of the hybrid power plant of between 3.25 Gwh and 2.4 GWh, depending on the share of wind and PV in the park. Energy costs were varied between 7 €ct/kWh and 3 €ct/kWh, which reflects the range of typical LCOE values for the present and the near future. Transformer customer prices are difficult to estimate since in many cases, custom-built or second-use units with unlisted prices will be used in commercial projects. In accordance with Testa et al. (2013) and own experience, the transformer cost was assumed to be 25 €/kVA for transformers in the 2 MVA range. The power plant lifetime was assumed to be 20 years.

For this evaluation, the scenario with an accepted energy loss of 0.5 % was used. Depending on the PV / wind ratio, this leads to a possible reduced transformer size of merely 61.9 % of the total nominal power of the VRE in the best case, translating into cost savings of up to 19050 €. For other PV / wind ratios, the possible transformer undersizing and the consequent cost savings are less pronounced.

On the other hand, the curtailment losses of 0.5 % lead to reduced revenue from energy sales which accumulate over the course of 20 years. These losses vary depending on the electricity price. For easier analysis, prices were assumed to be the same for electricity from PV and from wind power. However, the different specific yield of

PV and wind power plants results in slightly higher financial losses for a hybrid power plant with a larger wind part for an equal relative loss of energy.

Fig. 7 shows the comparison between the savings due to the reduced transformer size (black line) and the lost revenue due to energy curtailment (colored lines) for the 0.5 % loss level. If the black cost savings line is above the colored income loss lines, it is economically beneficial to reduce transformer cost and curtail energy. It can be observed that in the evaluated scenario, this is not the case for energy prices of 7 €ct/kWh. However, for energy prices of 5 or even 3 €ct/kWh, it does make sense to reduce transformer size and accept curtailment of 0.5 % of the total energy for most PV / wind ratios.

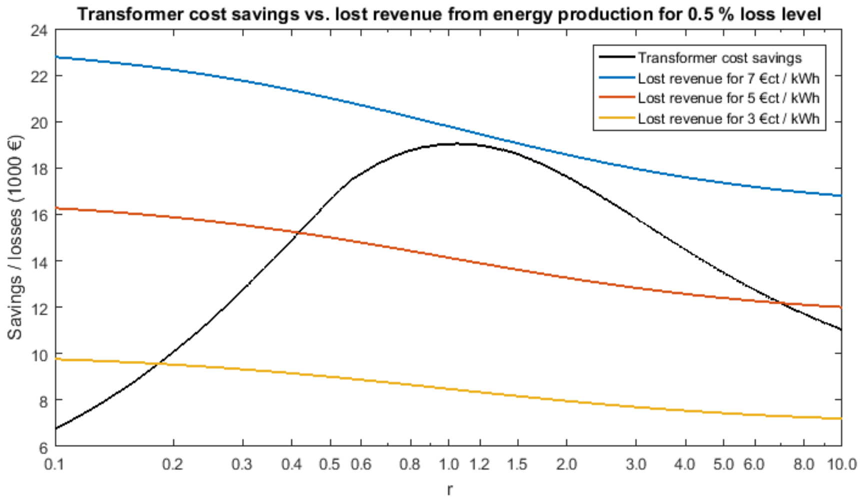

Fig. 7: Comparison of cost savings due to a reduced transformer size and lost revenue from electricity sale over 20 years in the case of 0.5 % energy curtailment

Understandably, it highly depends on energy prices if transformer undersizing is beneficial or not. As LCOE values are expected to evolve faster than transformer prices, the case for reducing transformer size will get even stronger in the future.

In order to put this result into a proper context, it must be taken into consideration that this evaluation only compares transformer cost and electricity prices. If power curtailment above a certain limit is accepted, other cost-reducing factors might include cables, switchgear, or even common power converters for wind and PV with reduced nominal power. Additionally, the benefits of a lower initial investment in terms of interest payment should be considered. On the other hand, higher expenses for safety measures such as a reliable and fast common park controller might arise.

The evaluation was only performed for the case of an accepted curtailment level of 0.5 % of the total produced energy. This is most probably not the cost-ideal scenario. In future studies, it should be evaluated which transformer rating and which level of curtailment gives the economically optimal results. However, it should not be forgotten that this kind of exercise will always be site-specific and lead to different results for each renewable energy project.

6. Conclusions and Recommendations

High-resolution feed-in data of a combined PV / wind power plant was recorded and evaluated for a timespan of one year. The evaluation of this data supports former findings that the simultaneity of production is low for most sites in Europe. Further analysis shows that less than 2 % of energy is lost due to curtailment for an energy cut-off at as low as 50 % of the total nominal power for the combined PV / wind power plant of the study case. The ideal ratio between PV and wind for minimum required connection power was found to be close to 1 for all considered curtailment scenarios. Additionally, it was shown that depending on investment cost and energy prices, it can be economically beneficial to reduce transformer size and accept a certain level of energy curtailment.

Future work could include more study cases and different sites. Additionally, economical cost / revenue comparisons should be done for different transformer ratings and energy curtailment levels.

An interesting consequence of these considerations could be the retrofitting of existing utility-scale VRE power plants. Planners and investors could specifically look for existing PV power plants and consider adding a certain amount of wind turbines to it (or the other way around) without increasing the nominal power of the PCC. Further economical evaluation in the future could focus on this aspect.

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