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Market value of PV battery systems for autonomous rural energy supply

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Abstract

Solar photovoltaics (PV) panels in combination with batteries are often proposed as a solution to provide stable power supply in rural areas. PV generation is mostly dominated by the solar diurnal cycle and has, in some countries, already started to have influence on the daily price distribution on the electricity market.

In this work, we study the performance and optimisation of rural PV-battery hybrid systems in a future renewable Polish power system. We use data on generation potentials to study PV and battery deployment. Together with a power system optimisation and dispatch model for the Polish power system, we study market values when selling at the national market for different CO_2 price scenarios. We show that optimal orientations with respect to tilt/azimuth are subject to change as the PV share grows and that the benefit from batteries grows for higher shares of renewables.

Keywords: energy storage; photovoltaics; battery, hybrid power system

1. Introduction

Around the world, large amounts of renewable generation capacities have been installed. Major aims behind transformations of power systems are climate change mitigation and increased sustainability.

Climate change has direct effect on renewable potentials [1,2] and the exploitation of renewables has the reverse effect of mitigating climate change. Wind, hydro and photovoltaics (PV) are the major renewable technologies. PV, unlike wind and hydro, is due to its comparably low investment barrier considered to be ideal for decentrally organized energy systems, where electricity is created and consumed locally. However, its generation potential is mostly dominated by the diurnal cycle and therefore neither dispatchable nor able to provide a constant baseload. Due to the characteristics of PV power generation, batteries are seen as a natural complementary to PV panels. Most promising are lithium-ion batteries, which are already used in many technological devices as of today, but

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are mostly not cost-competitive for grid storage application and whose non-linear behaviour (e.g., aging, self-discharge) is not fully understood.
Other options to partially integrate renewable energy include system-friendly renewables [3], optimal angle/tilt combinations of solar PV modules [4] demand side management [5], transmission grid extensions [6] or sector coupling [7,8].
Hybrid systems to combine different renewable sources have seen certain attention in the research community as well. Common combinations include PV and hydro [9-11] or wind-PV-hydro [12].
In this paper, we investigate three aspects: First, we investigate the cost-optimal generation mix in a Polish power system in dependency of the CO_2 price. Second, we study market values of rural PV systems in dependency of tilt/azimuth for different CO_2 prices, where these local PV systems are treated as a price maker and prices are taken as local marginal prices from the system optimisation.
Third, we investigate the potential benefit of batteries on the market value of PV for two CO_2 price scenarios.

2. Data

Time series of renewable generation for wind and photovoltaics, which were used in the system optimisation of the Polish power system, were obtained from the open power system database (open-power-system-data.org). For decentral energy supply, we investigated different azimuth/tilt combinations with respect to their usefulness for installing PV panels in terms of the slope and aspect of the roof, as well as the potential shading (Fig. 1). The analysis of corresponding potentials involved around 1900 buildings from the municipality of Piechowice (area 43.22 km^2, coordinates 505120N, 15378E; PL92: N: 328869340234, E: 255802263661), Poland. Potential tilts and azimuths were divided into 5 estimates for azimuth: E, SE, S, SW, W as well as 13 estimates of tilts in 13 steps by 5° in the range of 2.5° to 62.5°

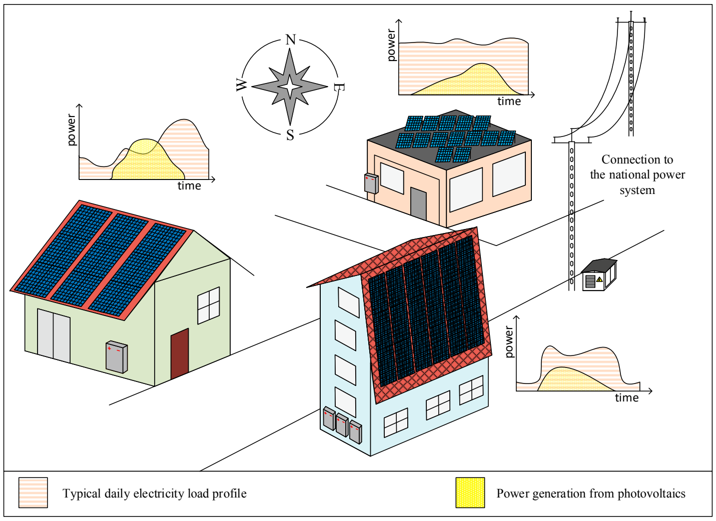

Fig. 1. Conceptual design of rural energy supply.

3. Methodology

We model the Polish power system via a linear program that minimises system cost. It is treated as an island system, i.e., exchange with neighboring countries is not considered. Furthermore, transmission constraints within the country are neglected (copperplate approximation). The objective reads:

$$\min_{g,G} \left(\sum_s c_s G_s + \sum_{s,t} o_s \, g_s(t) \right) \quad (1)$$

Here, c_s are the investment costs for generation capacity, o_s are the marginal costs of energy generation, G_s are the capacities of generators and g_s are the time series of dispatch. The index s runs over all considered energy technologies, e.g. wind, PV, conventional sources and batteries. A list of all energy carrier types used, the corresponding modelling details as well as their cost assumptions are given in Table I. The dispatch of hydro and bio power is not explicitly optimised. Instead, they are assumed to provide a constant baseload.
In addition to the objective, multiple constraints have to be satisfied:
To ensure stable power system operation, the demand must be matched by the actual power generation and/or storage flows at all times:

$$\sum_s g_s(t) - d(t) = 0 \leftrightarrow \lambda_t \ \forall t \tag{2}$$

where d is the demand. λ_t is the shadow price that is used as a market price to calculate market value in the second part of the results section.
The dispatch g_s of a generator or storage unit is constrained by its maximal capacity G_s multiplied by the corresponding hourly capacity factor $\overline{g_s}$, which is for renewable sources determined by the weather:

$$0 \leq g_{s,t} \leq \overline{g_{s,t}} G_{s,t} \ \forall t, s \tag{3}$$

The hourly capacity factor time series per renewable technology is based on historical data, i.e., the distribution of capacities within the country reflects the historical distribution.
Maximum capacities are assumed to be unlimited. For conventional generators, dispatch is purely constrained by the installed capacity, i.e. $\overline{g_s}(t) = 1.0$.
Storage consistency is ensured via the storage state of charge $SOC_{s,t}$ dispatch constraint:

$$SOC_{s,t} = \eta_0 SOC_{s,t-1} + \eta_1 g_{s,t}\ store - \eta_2^{-1} g_{s,t,} dispatch \ \forall s, t > 1 \tag{5}$$
$$SOC_{s,t} = SOC_{|t|} \tag{6}$$

where η_0 describes standing losses and η_1 and η_2 efficiencies of the corresponding charging and discharging processes. In addition, a cyclic state-of-charge is enforced.

4. Cost assumptions

Cost assumptions have been adopted from a publication by JRC [14]. They are briefly summarised in Table I. Annualised cost are calculated by assuming an annuity of 8.6% for all assets except PV, where the annuity is assumed to be 5.7%.

Table 1. Annualised cost assumptions for generation and storage technologies originally based on value estimates from JRC.

Technology	Overnight Capital Cost [Euro/GW/a]	Marginal Generation Cost [Euro/MWh]	Efficiency Dispatch/Uptake
OCGT	49.400	187.0	0.39
Onshore Wind	127.450	0.015	1
PV	61.550	0.010	1
Lignite	159.000	33.0	0.38
Hard Coal	133.200	45.0	0.39
Battery	120.389	0	0.900/0.900

5. Results

First, we analyse the results of the optimisation of the Polish power system.
Fig. 2 (left) shows the Polish generation mix in dependency of the CO_2 price as a result of the previously introduced optimisation problem. It is shown that at diminishing CO_2 prices lignite is the most competitive technology but is replaced by hard coal as CO_2 prices rise. Above prices of 20 Euro per ton, renewables become cost-competitive

replacing lignite, while the share of hard coal continues growing, as well. The share of hard coal continues to grow until CO_2 prices are slightly above 30 Euros per ton, while lignite is completely irrelevant at this point. In addition, it can be observed that relative market values (calculated according to Eq. 6) of renewables decrease as generation shares increase. This can be attributed to profile-related values [13], as growing shares of renewables exhibit greater influence on price patterns. PV has a relative market value of around 80% at a CO_2 price of 0 Euros/ton, which grows slightly to around 90% at 20 Euro/ton, but monotonously decreases afterwards, as PV shares start to grow rapidly. For wind, relative market value monotonously decreases with growing CO_2 prices, but starts from a comparably high level of more than 120% and, once CO_2 prices reach values above 20 Euros/ton, stays a constant number of percentage points above the value for PV.

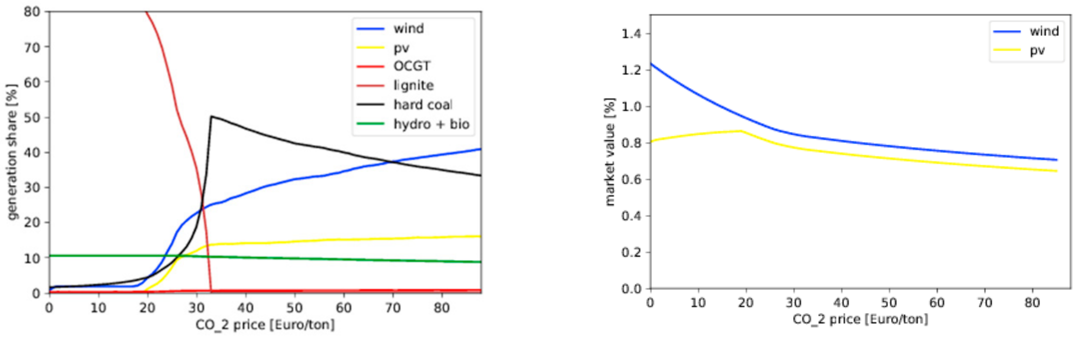

Figure 2: Left: Optimal generation mix in dependency of the CO_2 price. Right: Relative market value of wind and PV in dependency of the CO_2 price.

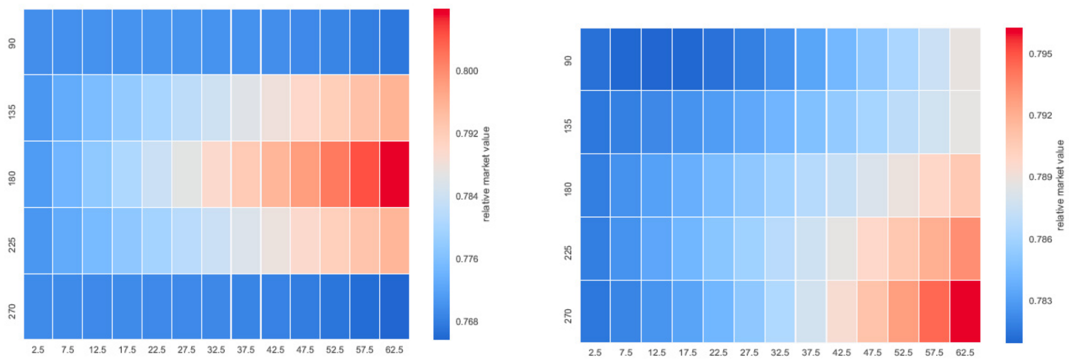

Figure 3: Relative market values for CO_2 price of 0 and 30 Euro/ton (left / right).

Next, we study the market value of PV systems in dependency of tilt and azimuth. First, we cost-optimise a purely decentral PV-battery supply (i.e., no exchange with the national grid) for the described municipality of Piechowice, where we limit installed capacity per tilt/azimuth combination to 1 MW and find an installed capacity of 16.5 MW distributed among combinations as well as a battery with an energy capacity of 104.6 MWh. Capacities are installed south-facing (azimuth 180 degree) and south-east facing (azimuth 135) at high tilts of 30 degree and more, where capacity factors are highest and therefore levelised cost of electricity is lowest. Different tilts and azimuth have different feed-in profiles causing different values of generated energy. Taking shadow prices λ_t from the system optimisation, one can calculate the relative market value ϑ (relative to a constant feed-in profile) as

$$\vartheta = \frac{\sum_t g_t \lambda_t}{\sum_t g_t \overline{\lambda_t}} \tag{7}$$

where $\overline{\lambda_t}$ is the average price.

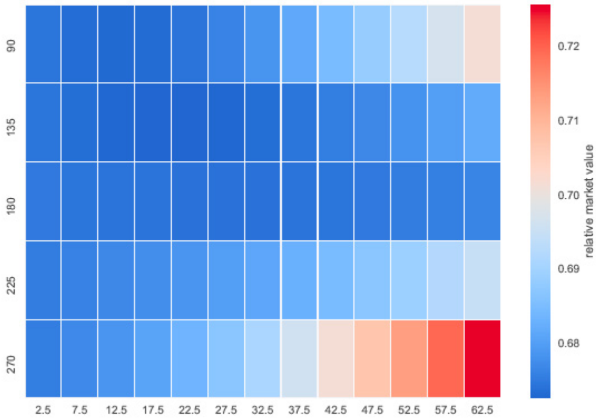

Figure 4: relative market value for CO_2 price of 80 Euro/ton.

Fig. 3-4 show relative market value for three different CO_2 prices of 0, 30 and 80 Euro/ton. At a CO_2 price of zero, south-facing modules of high tilt have highest market values. At these CO_2 prices, virtually no PV system is within the optimal national mix, hence no influence of PV on price statistics is exerted. The high market value of PV with this tilt/azimuth combination indicates a large agreement with load patterns, which dominate prices. At prices of 30 Euro, where PV has a share in the generation mix of approximately 15% and wind of another 25%, the picture has already changed: now, west-facing modules are optimal, albeit differences are small. At a price of 80 Euros, this pattern is even further pronounced and relative differences in market value are up to 10%. At those prices, wind and PV contribute around 60% of the generation mix. It can therefore be concluded, that price patterns under these circumstances are dominated by generation instead of demand.
Next, we allow for additional battery storage to increase the market value of PV without considering the cost of the battery.
Fig. 5 shows relative market value of PV power in combination with a battery of different energy capacities. No limits on charging/discharging rates are assumed. In addition, the battery can only store produced PV power, but sell it at any time.
At 30 Euro/ton, relative market value increase is around 20% for an energy capacity that is equal to the nominal PV capacity times 1 hour. At a storage capacity of 6 hours times the nominal capacity, the market value is roughly doubled.
For a CO_2 price of 80 Euro/ton, where renewables have considerable influence on market prices, the market value already doubles at an energy capacity of 1 hour times the capacity and a 6-hour storage increases it by around 5 times.

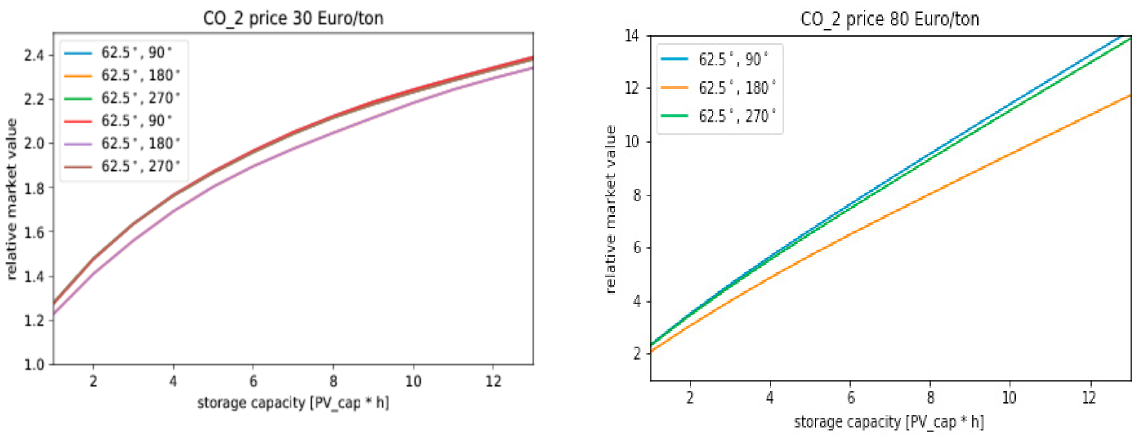

Figure 5: Relative market value of PV battery systems in dependency of the storage size.

6. Discussion and conclusions

In this paper, two aspects are investigated. First, the market value of PV panels for different tilt/azimuth combinations is studied. For low CO_2 prices, market values tend to be highest for south-facing modules. This can likely be attributed to the resemblance of generation profiles of south-facing modules to demand patterns. If CO_2 prices increase, a paradigm shift can be observed: west-facing modules have the highest relative market value. This is likely because prices are not dominated by the demand anymore, but instead by non-dispatchable generation. Furthermore, it can be concluded from this fact that the PV time series, which influences price statistics, is likely dominated by south-facing modules.

However, relative market value differences between different combinations of tilt and azimuths remain in all cases below 10%. Therefore, it seems likely that levelised cost of electricity differences have the largest impact on profitability of PV systems and concrete feed-in pattern differences are of minor importance.

Second, the effect of a battery on the market value of solar PV is shown.

Especially at high CO_2 prices of 80 Euro/ton, where renewables wind and PV contribute a noticeable share to the overall generation mix in the national power system of around 60%, batteries provide a huge increase in market value, which is around 4-5 times higher than at a CO_2 price of 30 Euro/ton.

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