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A regional optimisation of renewable energy supply from wind and photovoltaics with respect to three key energy-political objectives

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ABSTRACT

Currently, most PV (photovoltaic) modules are aligned in a way that maximizes annual yields. With an increasing number of PV installations, this leads to significant power peaks and could threaten energy policy objectives. Apparently sub-optimal inclinations and azimuth angles of PV plants on building roofs could counteract such tendencies by achieving significant temporal shifts in the electricity production. This paper addresses the potential of these counter-measures by evaluating the optimal regional mix of wind and PV installations with different mounting configurations in order to locally generate the annual electricity demand. It does so by adhering to three distinctive energy policy goals: economic efficiency, environmental sustainability and security of supply. The hourly yields of wind parks and nine PV orientations are simulated for four representative NUTS3-regions in Germany. These profiles are combined with regional electricity demand profiles and fed into an optimisation model. As a result, the optimal installed capacity for PV for every possible configuration – determined by inclination and azimuth angles – and the optimal installed capacity of wind power are obtained. The results indicate that the optimal mix differs significantly for each of the chosen goals, depending on regional conditions, but also shows a high transferability of general statements.

1. Introduction

1.1. Motivation

A combination of ambitious European and national goals alongside strong economic support policies have led to a rapid expansion of onshore wind and PV (photovoltaic) capacities in Germany. From total installed electricity generation capacities for PV and onshore wind of 2.1 and 18.4 GW respectively at the end of 2005, the latest statistics report 35.9 and 34.7 GW respectively at the end of 2013 [1]. Despite a short-term drop in the expansion rate in 2013, further progress towards national renewable energy goals means that this trend is very likely to continue in the near and medium term future. The rapid development of decentralized PV systems, in Germany fuelled by the Renewable Energy Law, has led to drastic cost reductions and associated adjustments to the feed-in tariffs in Germany in recent years. In countries (such as Germany) where grid parity has been achieved for residential electricity customers (who pay around 31€ct/kWh for their electricity [2]), compared to current electricity generation costs of around 12 €ct/kWh [3] for new PV plants in Germany, the economic attractiveness of generating PV-electricity for self-consumption has drastically improved.

From a plant operator's perspective, the LCOEs (levelised costs of electricity) are the conventional economic yardstick with which to assess generation technologies like PV-systems and wind turbines [4]. One key determining factor for the LCOEs of PV and wind, as well as the investment and running costs, is the absolute electricity generated over a year, which depends largely on the location (annual solar irradiance, average wind speed), applied technology and orientation/hub height. Whilst previously the focus has been on the minimization of LCOEs based on reducing costs and maximizing the (specific) system output, there are increasingly more reasons why this approach might not be satisfactory. For example, the electricity network may not be able to cope with the generation profile (peak power and power gradients) in its present condition – in other words the system costs are actually much higher, when the necessity of network expansion and balancing power are considered as has been shown by Ueckerdt et al. [5].

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Hence an orientation of PV-systems and combination with wind turbines, which appears economically suboptimal from an investor's point of view, may lead to lower overall system costs and/or greenhouse gas emissions, and/or a higher level of energy security, when all aspects are considered.

1.2. Literature review

The diverse and in some respects contradictory criteria with which to optimise energy systems, and the associated trade-offs, are discussed by Østergaard [6]. He mentions several criteria, including renewable energy shares, primary energy consumption, economic and social costs, carbon dioxide emissions, as well as the associated imports/exports and requirements for reserve power plant capacities. These criteria are applied to an energy system model for Western Denmark, and a multi-criteria decision analysis is then used to evaluate the three scenarios. The different optimisation criteria yield quite different results. A crucial aspect seems to be whether or not the region is considered in island or connected mode, or a combination of the two; in the former case large expansions in renewables generators are not feasible unless spatial (networks) and temporal (storage) relocation infrastructure are also developed.

The complementarity of solar and wind resources can be exploited to smooth the generation curve, as these two resources generally exhibit quite different availabilities [7–9]. Budischak et al. [7] developed a model to analyse the total system costs of providing almost 100% of electricity from renewables to the PJM (Pennsylvania-New Jersey–Maryland) Interconnection system in the USA. Their model minimizes total system costs for electricity supply, based on a parameterisation for the years 2008 and 2030, and treating the electricity network as a “copper plate”. The main result is that the least-cost system has excessive renewable generation capacities – enough to generate three times the total demand due to the reduced storage requirement and thus lower total system costs – which would be used to meet some of the thermal loads (not considered in the article).

Hoicka and Rowlands [8] employ non-dimensionalised electricity production indices for four locations in Ontario, Canada, and assess various technology and location combinations. They conclude that the combination of these two technologies in one location does indeed smooth production, which is further improved when two resources and locations are considered. There is no additional benefit (but neither a necessary disadvantage) in terms of further residual load smoothing from a geographic dispersal of the plants, i.e. wind and solar in different locations, although electricity networks were not explicitly considered in the contribution, so this conclusion should be treated with caution.

Lund [9] examines the large-scale integration of the RES (renewable energy sources) wind, PV and wave into the electricity supply system of Denmark. The energy simulation model EnergyPLAN is employed to determine the percentage of RES that could be integrated, by avoiding excess electricity production and considering requirements for additional ancillary services. He concludes that the optimal mixture is with onshore wind producing around 50% of the total, with the proportions of wind and PV depending on the total renewable fraction of electricity generation: lower overall RES fractions favour higher PV penetrations and vice versa. The approach is a purely technical one, i.e. it identifies optimal combinations of RES without considering costs and other environmental, social, and practical aspects.

Several authors have analysed the technical potential to optimise the sizing and configuration of PV systems [10–12]. For example, Weniger et al. [10] optimise the sizing of residential PV and battery systems with a view to maximizing the self-consumption rate (defined as the fraction of PV electricity that is used for own consumption) and degree of self-sufficiency (defined as the fraction of the total (annual) electricity consumption delivered by the PV/battery system). Widén et al. [11] focus on the technical potential for matching the electricity generation from PV with the load profile. As well as considering different sizing (both absolute capacity and PV-panel-to-inverter ratios) and orientation (azimuth angle, inclination), the approach considers two other options for load matching, namely DSM (demand side management) and electricity storage. The authors apply the method to several typical load profiles for northern latitudes but suggest that the method could easily be employed elsewhere. The main findings are that storage is the most attractive option at higher penetration levels, whereas DSM is as effective or even superior at lower penetrations. Interestingly, the authors report that “although optimisation of the aggregate PV output profile through orientation of subsystems suggests an east-west orientation at high penetration levels, the impact […] is quite small compared to the other options”. Mondol et al. [12] undertake a purely technical analysis by employing a developed TRNSYS simulation model to optimise the setup of grid-connected photovoltaic systems. The study also shows that there are often regional and local deviations from maximum yields by facing directly south (azimuth angle of 90°) and with an inclination angle of 30°, such as for a location in Ireland where the optimal inclination was found to be 20°. Finally, in their investigation of mismatch factors for ZEBs (zero-energy buildings), Lund et al. [13] find that the challenge of integrating large amounts of PV with battery storage is best addressed at the utility level.

In an unpublished study, Tröster and Schmidt [14] investigate the impact of PV module orientation on grid operation by analysing several discrete orientation configurations for the city of Aachen in Germany. They conclude that east-west facing plants (or similar) have capacity factors not much lower than south facing plants, as well as power gradients and peak power outputs significantly lower, which has advantages for the electricity network and the integration of PV electricity. The authors conclude that there is no obviously optimal system orientation as this depends on the priorities and the prevailing conditions in the specific location.

Other authors also consider economic aspects in their approach to setup optimisation [15–17]. Mondol et al. [15] further develop their methodology from Mondol et al. [12] to consider economic aspects of PV electricity generation and thus investigate the scope for matching the generation profile of the PV system to the load. The results demonstrate the sensitivity of PV-electricity generation costs to the setup of the system (especially the ratio of the PV module to the inverter) as well as suggesting that feed-in of this electricity should be avoided when the tariff lies below the electricity price.

Hartner et al. [16] also investigate the effect of alternative approaches/orientations on the total system costs. The authors argue that an energetically sub-optimally oriented PV system (i.e. not south and 30° inclined) could still be environmentally favourable in terms of fuel costs and emissions, depending on the electricity from the system that it displaces. The authors thus equate the market value of PV-electricity with the marginal costs of the displaced power plant park, hence neglecting system integration costs in the form of network expansion and balancing power. For this purpose an optimisation power plant dispatch model of the German-Austrian power plant park is developed. The basis data (RES feed in and load profile) is taken from 2012 and the two countries are disaggregated into 23 regions (about the size of a federal state). The results show that only with very large capacity additions (over 100 GW) of PV does the energetic optimum deviate from the market optimum. Furthermore, with an unlimited availability of storage and a completely uncongested electricity network, the